Geology of the Murray Basin, Southeastern Australia

BMR Bulletin

235

C.M. Brown & A.E. Stephenson

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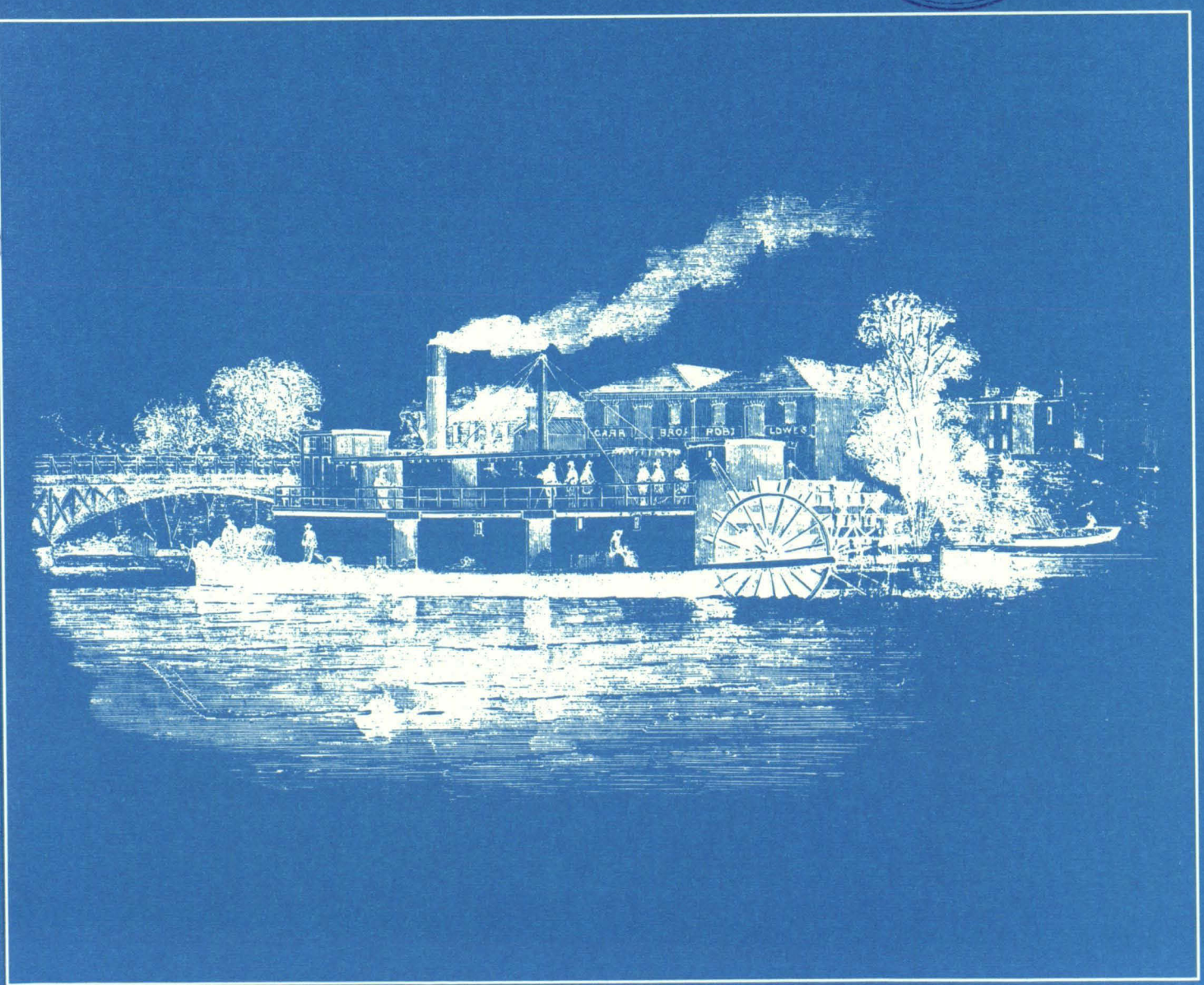

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Dedicated to the life of

Campbell McInnes Brown

(1949–1991)

This Bulletin documents the results of much of the work of Campbell Brown during the last ten years of his life, which ended prematurely on 2 June 1991.

In 1979, under the control of the then Commonwealth–States Steering Committee on the Murray Basin (later to become the Murray–Darling Basin Commission Groundwater Working Group), Campbell was given the task of producing a structural and stratigraphic framework as a basis for the Murray Basin Hydrogeological Project, a long-term study undertaken by South Australia, Victoria, New South Wales and the Commonwealth, in response to increasing concern about environmental degradation in the Basin.

Campbell planned, coordinated and carried out the first integrated study of surface and subsurface geological and hydrogeological data for the entire Basin. His stratigraphic framework, presented in 1983, is impressive in its simplicity of purpose and level of rigorous detail. Its acceptance, and ability to accommodate new data collected as the project advanced, are a tribute to Campbell's skills as a stratigrapher and sedimentary basin analyst.

One of Campbell's major research contributions was to elucidate, within the Murray Basin, the relationship between basin structure and sediment stratigraphy and the occurrence and movement of groundwater. This work, documented in several papers, bridged an interdisciplinary gap, and has enabled the investigation of the serious salinity problems of the Basin to proceed with confidence.

This Bulletin will be a benchmark text for many years. It will be a lasting reminder of the achievements of an all-too-short life, and a tribute to the perseverance of a dedicated scientist, Campbell McInnes Brown.

Department of Primary Industries & Energy

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

BULLETIN 235

BMR PUBLICATIONS COMPACTUS
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Geology of the Murray Basin Southeastern Australia

C.M. Brown & A.E. Stephenson

(Groundwater Program, BMR)

Published as a contribution to the joint Commonwealth and States Murray–Darling Basin Hydrogeological Project

AUSTRALIAN GOVERNMENT PUBLISHING SERVICE
CANBERRA

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ISSN 0084 – 7089
IBSN 0 644 13782 7

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Department of Primary Industries and Energy

Minister for Resources: The Hon. Allan Griffiths, MP

Secretary: Geoff Miller

Bureau of Mineral Resources, Geology and Geophysics

Director: R.W.R. Rutland AO

Editor: K.H. Wolf – see also Acknowledgements

Line figures prepared by Lindell Emerton, BMR Cartography Section

Word-processing and desk-top publishing by C.M. Brown, BMR Groundwater Program

Cover: The Lady Daly, a river steamer on the Murray River. The scene is from a wood engraving, printed in the London Illustrated News Supplement of December 5, 1863 (supplied by the National Library of Australia).

Printed in Australia by Imprimatur Press

PREFACE

Joint Commonwealth – States Murray Basin Hydrogeological Project

The Murray Basin is one of the most economically important agricultural regions in Australia, and currently generates several billion dollars in annual income. Major irrigation schemes, towns and cities (including Adelaide) now depend on the limited water resources of the Murray River and its tributaries throughout the southeastern highlands. In addition, large areas of the basin rely on bore water for stock and human consumption, and locally for irrigation. Clearance of natural vegetation and irrigation have, however, increased infiltration to underlying sediments, resulting in rising groundwater levels and discharge of saline water into the landscapes and river systems of the basin. The accelerated emergence of these problems now threatens the economy and natural environments of the basin. Extensive areas of formerly productive agricultural land are being turned into saline wastelands, and the quality of drinking water has deteriorated in many towns and cities which depend on the Murray River for their supplies.

The Commonwealth and States of South Australia, New South Wales, and Victoria now recognise the urgent need to develop coordinated strategies for salinity management in the Murray Basin. The joint Commonwealth – States Groundwater Working Group of the Murray – Darling Basin Commission was subsequently established in recognition that most salinity problems are essentially groundwater-related, and that an understanding of the groundwater mechanisms involved in salinisation is essential when formulating salinity management priorities and options. The Murray Basin Hydrogeological Project forms part of the work plan of the Groundwater Working Group, and is being undertaken collaboratively by BMR, the Geological Surveys of South Australia, Victoria and New South Wales, the New South Wales and Victorian Departments of Water Resources, and the Rural Water Commission of Victoria. The primary objective of the hydrogeological project is to provide a scientific knowledge base for the development of strategies aimed at managing the natural groundwater resource and salinity problems of the basin.

At an early stage of the hydrogeological project, it was recognised that a knowledge of the stratigraphic and structural framework of groundwater is an essential prerequisite to understanding both the hydrogeological systems and processes which have contributed to the development of present-day salinity problems. The geological surveys and water authorities in each State have previously undertaken extensive investigations of groundwater, but no basin-wide geological study has previously been attempted. BMR was therefore requested by the Groundwater Working Group to undertake a comprehensive study of the geology of the Murray Basin, by examining it as a single entity, unencumbered by State boundaries. This document summarises the results of that geological study.

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ABSTRACT

The Murray Basin extends over 300 000 km^2 of inland southeastern Australia, is flanked by subdued mountain ranges, and forms a low-lying saucer-shaped basin with thin flat-lying Cainozoic sediments. Over the past 100 years, the Murray Basin has become one of the most important agricultural regions in Australia. Unfortunately it is also a closed groundwater basin, which consists of a thin sequence of sediments containing a number of aquifer systems, with little capacity to absorb additional recharge. Irrigation and clearing of natural vegetation have increased recharge to these aquifer systems. Resultant rising groundwater levels and discharge of saline water into the landscapes and river systems of the basin, have created salinity problems that threaten to have an increasingly adverse impact on both the regional economy and natural environments. Many of the reasons for salinisation lie in the subsurface geology, and can be related to the development of the structural and stratigraphic framework of the basin over the past 60 Ma. Knowlege of these is a prerequisite to understanding hydrogeological systems and processes contributing to the salinity problem. This document summarises the geology of the Murray Basin.

Beneath the Murray Basin, geophysical and borehole evidence indicates that folded and partly metamorphosed Proterozoic and Lower Palaeozoic basement is block-faulted, and that the Cainozoic sequence is locally underlain by poorly defined infrabasins preserved in graben-like troughs. These contain thick sequences of Devonian to Lower Carboniferous sedimentary rock and discontinuous, erosional remnants of Upper Carboniferous, Permian, Triassic and Cretaceous platform-cover sediments.

The Cainozoic succession of the Murray Basin forms an extensive blanket of sediment, with a maximum thickness of about 600 m preserved in the deeper, central-western parts of the basin. A subsidiary depocentre with over 400 m of sediment underlies the central-west Riverine Plain, but in most northern, eastern, and southern parts of the basin the sediment succession is generally less than 200–300 m thick, and could be more accurately described as forming a thin platform-cover succession rather than a true basinal sequence. Within the Tertiary succession at least three major depositional sequences (Paleocene–Eocene to Lower Oligocene, Oligocene–Middle Miocene, and Upper Miocene–Pliocene) have been identified. Each sequence consists of a package of genetically related formations separated by disconformities. Poorly consolidated, non-marine sand, silt, clay, and carbonaceous sedimentary rocks predominate in the east and north, but each of the depositional sequences includes weakly lithified marine sedimentary rocks in central and southwestern areas. The stratigraphy translates into a number of regional aquifer systems, confining layers and permeability barriers to groundwater flow, each with distinctive characteristics.

In the Mallee region of the west, the Tertiary sediments of the Murray Basin are almost entirely concealed beneath a mainly 'fossil' arid and semi-arid landscape of Quaternary aeolian dunefields, with minor fluvial and lacustrine morphostratigraphic units. Farther east, where the basin and adjacent highlands are drained by the Murray, Murrumbidgee and Lachlan Rivers, the Tertiary sequence underlies flat-lying fluvio-lacustrine and minor aeolian sediments of the semi-arid landscape of the Riverine Plain. Within the Mallee and Riverine Plain landscapes, active and 'fossil' (currently inactive) groundwater discharge lake complexes can be identified by characteristic assemblages of Upper Quaternary sediments forming stranded lake floors, gypsum flats, salinas, gypsum and clay pellet dunes and lunettes. These have developed within low-lying areas during the past 0.5 Ma. Their extent indicates the presence of widespread salinisation under 'natural' conditions at times in the recent geologic past.

The main emphasis of the study is on improving our understanding of the geological context of groundwater and surface discharge in the Murray Basin, but at an early stage the scope of the study was expanded to include reference to other mineral resources. These include Cainozoic limestone, alluvial gold, kaolin, heavy minerals, gypsum and halite deposits. The Tertiary succession contains extensive deposits of currently sub-economic brown coal, underlain by Upper Permian coal in the Oaklands Infrabasin in New South Wales. The Cainozoic Murray Basin is not prospective for hydrocarbons, but several concealed pre-Cainozoic infrabasins remain poorly investigated.

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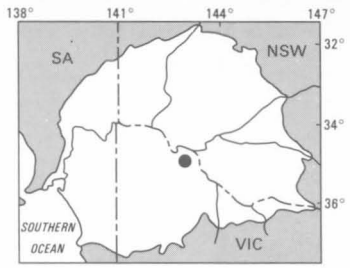


Fig. 1. Saline groundwater discharge within aeolian Mallee landscape of Manangatang region (SWAN HILL), northern Victoria.

INTRODUCTION

This Bulletin summarises the geology of the Cainozoic Murray Basin, a major groundwater basin located in the semi-arid zone of southeastern Australia (Fig. 2). The study was undertaken at the request of the Groundwater Working Group of the Murray–Darling Basin Commission, to provide a comprehensive geological framework for the Murray Basin Hydrogeological Project – a long-term basin-wide study undertaken collaboratively by BMR; the Geological Surveys of South Australia, Victoria and New South Wales; the New South Wales and Victorian Departments of Water Resources; and the Rural Water Commission of Victoria.

The Murray Basin is one of the economically most important agricultural regions in Australia, but after just one hundred years of European development, groundwater-related salinisation of its landscapes and river systems threatens its economy and natural environments. The primary objective of the hydrogeological project is to provide a scientific knowledge base for the development of strategies to manage the natural groundwater resources and salinity problems. A major objective of this geological study has been to develop an understanding of the stratigraphic and structural framework of groundwater in the Cainozoic succession of the Murray Basin, by examining it as a single entity, unencumbered by State boundaries. The basin partly

underlies three States, and the geological surveys and water authorities in each State have undertaken extensive investigations of groundwater distribution, but no basin-wide geological study has previously been attempted. Various other aspects of the geology and hydrogeology have been reported in companion publications produced by BMR as contributions to the Murray Basin Project (Brown, 1980, 1983, 1985, 1988, 1989; O'Brien, 1981, 1986, 1989; Brown & others, 1982; Brown & Stephenson, 1985, 1986, 1989; Truswell & others, 1985; Stephenson, 1986; Evans & Brown, 1987; Evans & others, 1987, in press; Macphail, 1987, 1988a,b; Radke, 1987, 1990; Truswell, 1987; Brown & Evans, 1988; Brown, Kellett & Evans, 1988; Brown, Tucker & Anfiloff, 1988; Evans, 1988; Evans & Kellett, 1988, 1989; Kellett, 1988, 1989; Macphail & Truswell, 1988, 1989; Stephenson & Brown, 1988, 1989; Brown & Radke, 1989).

Scope and methodology of geological study

The long-term strategy has been to adopt a basin-wide approach, in order to provide a geological framework for the study of groundwater systems and processes which operate in the Murray Basin (Fig. 3). The specific aspects of the geological phase are documented in this Bulletin as follows:

Surface geology. Virtually the entire surface of the basin is mantled by Quaternary morphostratigraphic units. In recent years, these have received considerable attention from Quaternary sedimentologists, geomorphologists, soil scientists, and archaeologists. Emphasis has been placed on investigation of the sedimentological processes which have resulted in formation of lake systems and lunettes, including the role of fluctuating groundwater levels in the development of groundwater discharge complexes. These surficial units of the Murray Basin provide a record of palaeoclimatic and palaeohydrologic conditions over the past several hundred thousand years. For example, it is apparent from the distribution of gypsum flats and gypsum/clay pellet lunettes, associated with relict groundwater discharge complexes, that salinisation of the landscape has been considerably more widespread in the recent geologic past than it is at present. Rising groundwater levels are currently resulting in the re-activation of many former groundwater discharge sites. Mapping of morphostratigraphic units and relict groundwater discharge features of the basin can thus be used as a predictive technique to help identify those areas where there is a particular risk of future groundwater-related salinity problems. Descriptions of the Quaternary units of the surface of the Murray Basin are therefore included in this study.

Fig. 2. Locality map.

The distribution of surface Quaternary units is shown on the enclosed 1:1 000 000 scale geological map of the Murray Basin, which was compiled to a standard format and legend from photo-reductions of published 1:250 000 geological maps. Parts of the basin in New South Wales remain unmapped at 1:250 000; these were examined at reconnaissance level, suitable for reproduction at 1:1 000 000 (Brown & Stephenson, 1985). The map sheets examined were ANABRANCH, BALRANALD, POONCARIE, DENILIQUIN, HAY, BOOLIGAL, MANARA, MENINDEE. The geological mapping was based mainly on photo-interpretation of black-and-white aerial photographs of the RC9 Series (1:80 000), supplemented by minor traversing with four-wheel-drive vehicles. Black-and-white as well as colour LANDSAT images were used to identify additional trend lines and boundaries. The topographic base was compiled from maps of the 1:1 000 000 International Map of the World Series. Place names are spelt as in the Gazetteer of place names (available as computer output or microfiche from the Australian Surveying and Land Information Group – AUSLIG). The latitude and longitude of geographic names mentioned in the text are listed alphabetically

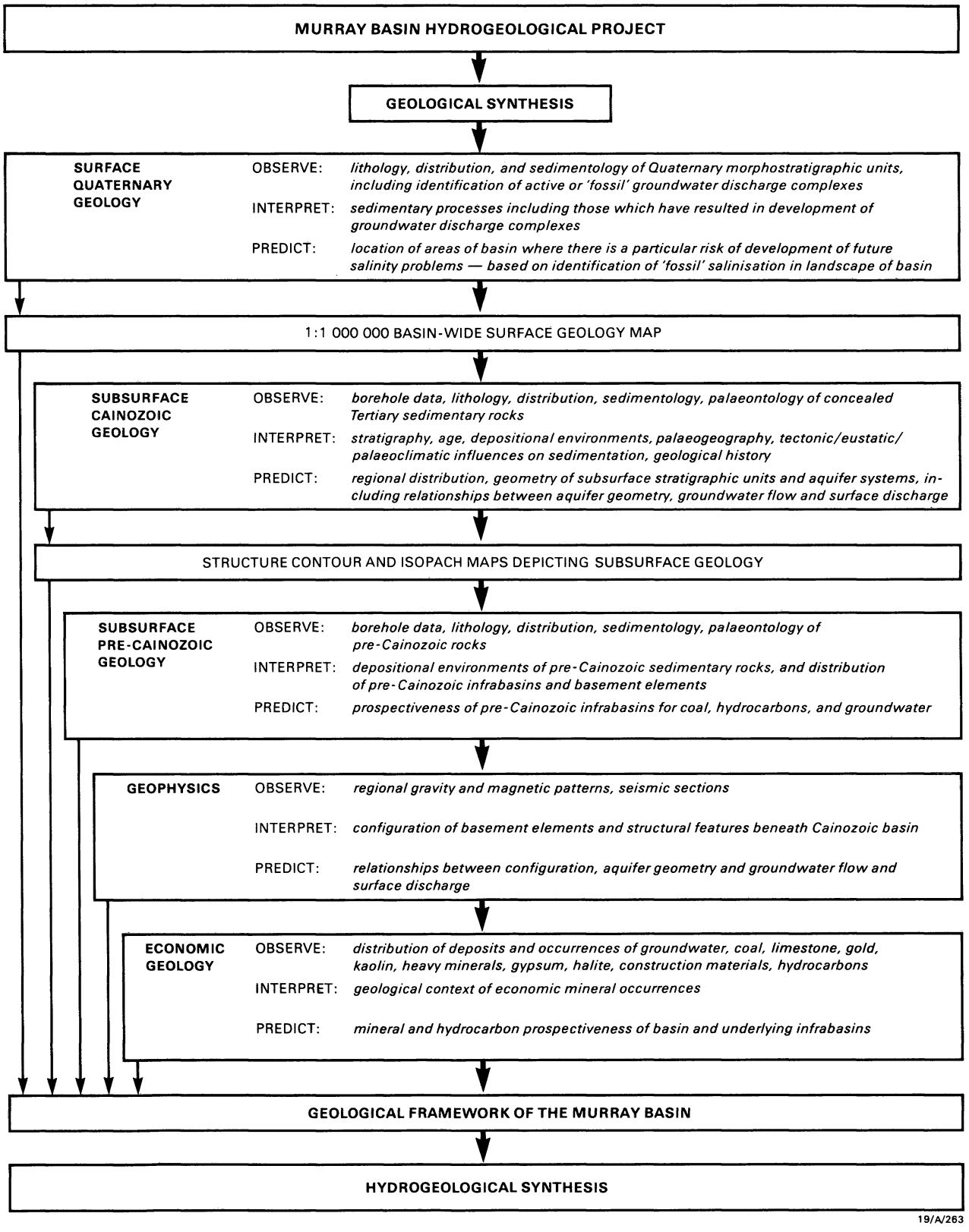


Fig. 3. Scope of geological phase of Murray Basin hydrogeological project.

in Appendix 1. An explanation of abbreviations used in the text is given in Appendix 3.

Subsurface geology. A major objective of the geological synthesis has been to establish a basin-wide subsurface stratigraphic framework by documenting the regional distribution, geometry and depositional environments of the Tertiary stratigraphic units, aquifers and aquitards of the basin. A knowledge of the evolution of the subsurface structural and stratigraphic framework, over the past 60 Ma, is a prerequisite to understanding the hydrogeological systems which have contributed to the development of present-day salinity problems. The Murray Basin sequence is only 200–600 m thick, and is largely water saturated. Additional groundwater storage capacity is limited and therefore groundwater levels have risen rapidly during the past one hundred years, following the clearance of natural vegetation. In places, the discharge of saline groundwater to the surface can be related to groundwater flow disruption created at permeability barriers formed by lateral changes in lithology. The Tertiary succession of the Murray Basin is almost entirely concealed beneath Quaternary morphostratigraphic units. Consequently, the development of a sub-surface stratigraphic framework has been based on facies analysis of lithologies obtained from borehole logs, in combination with limited palaeontological control. The borehole study involved interpretation and compilation of stratigraphic information from a dataset of several tens of thousands of unpublished water borelogs, stored in State survey and water authority archive files and retrieval systems, and made available by the organisations participating in the Murray Basin Hydrogeological Project. Approximately three thousand water bores, in addition to a small number of petroleum wells and mineral exploration bores, have been used as stratigraphic control points. The stratigraphic dataset was stored and maintained in computer databases and structure contour; and isopach maps of the major stratigraphic units and aquifer systems, included in the accompanying Plates, were generated using an automated contouring package. Descriptions of both the basin-wide stratigraphic framework and of individual stratigraphic units are contained herein. The results of the systematic compilation of borehole data – including the interpreted downhole stratigraphy of the 3000 boreholes, borehole locality maps, and data sources – have been published elsewhere in a separate subsurface stratigraphic database (Brown & Stephenson, 1986).

Development of a basin-wide stratigraphic framework necessitated revision of existing schemes. Many stratigraphic names, however, are entrenched in the geological literature of each individual State and, therefore, the existing detailed nomenclature has been retained where possible. The basic objective has been to clarify nomenclature in order to allow lithostratigraphic units to be placed in context within a basin-wide stratigraphic framework. In view of the profusion of local and regional stratigraphic schemes, which have previously been applied in the Murray Basin, an index of stratigraphic names is provided in Appendix 2.

Pre-Cainozoic geology. During the course of the study, it became apparent that the structural configuration of basement elements beneath the Murray Basin has influenced Cainozoic sedimentation patterns, and thus also aquifer geometry, and present-day groundwater flow and surface discharge patterns. For example, the Murray Basin is almost entirely flanked by subdued mountain ranges and forms a low-lying basin of internal surface and groundwater drainage. Consequently, groundwater is trapped within the basin, and can only escape either by discharge to the Murray River or to the landscape, followed by evapotranspiration and accumulation of salts. The structural configuration of the Proterozoic to Mid-Palaeozoic basement elements and pre-Cainozoic sedimentary rocks beneath the Murray Basin was therefore examined, as an aid to understanding groundwater flow patterns. In addition, the scope of the project was expanded to include reviews of the poorly known geology of underlying infrabasins. These contain Devonian to ?Lower Carboniferous, Upper Carboniferous to Lower Permian, Upper Permian, Triassic and Cretaceous sedimentary rocks (see Fig. 23). Details of boreholes encountering pre-Cainozoic rocks are given in Brown & Stephenson (1986).

Geophysics. Most basement features concealed beneath the Murray Basin have been identified mainly on the basis of regional gravity and aeromagnetic patterns, in combination with sparse seismic profiles and borehole control. In addition, regional total magnetic intensity imagery can be interpreted in terms of a number of concealed Proterozoic and Palaeozoic structural belts, as well as a number of cross-cutting lineaments (fracture sets). Most of these features, however, remain poorly known. As noted above, the configuration of basement features provides the primary control on the structural framework of the basin, and therefore influence aquifer geometry and present-day groundwater flow patterns. The geophysical datasets are summarised in the form of a

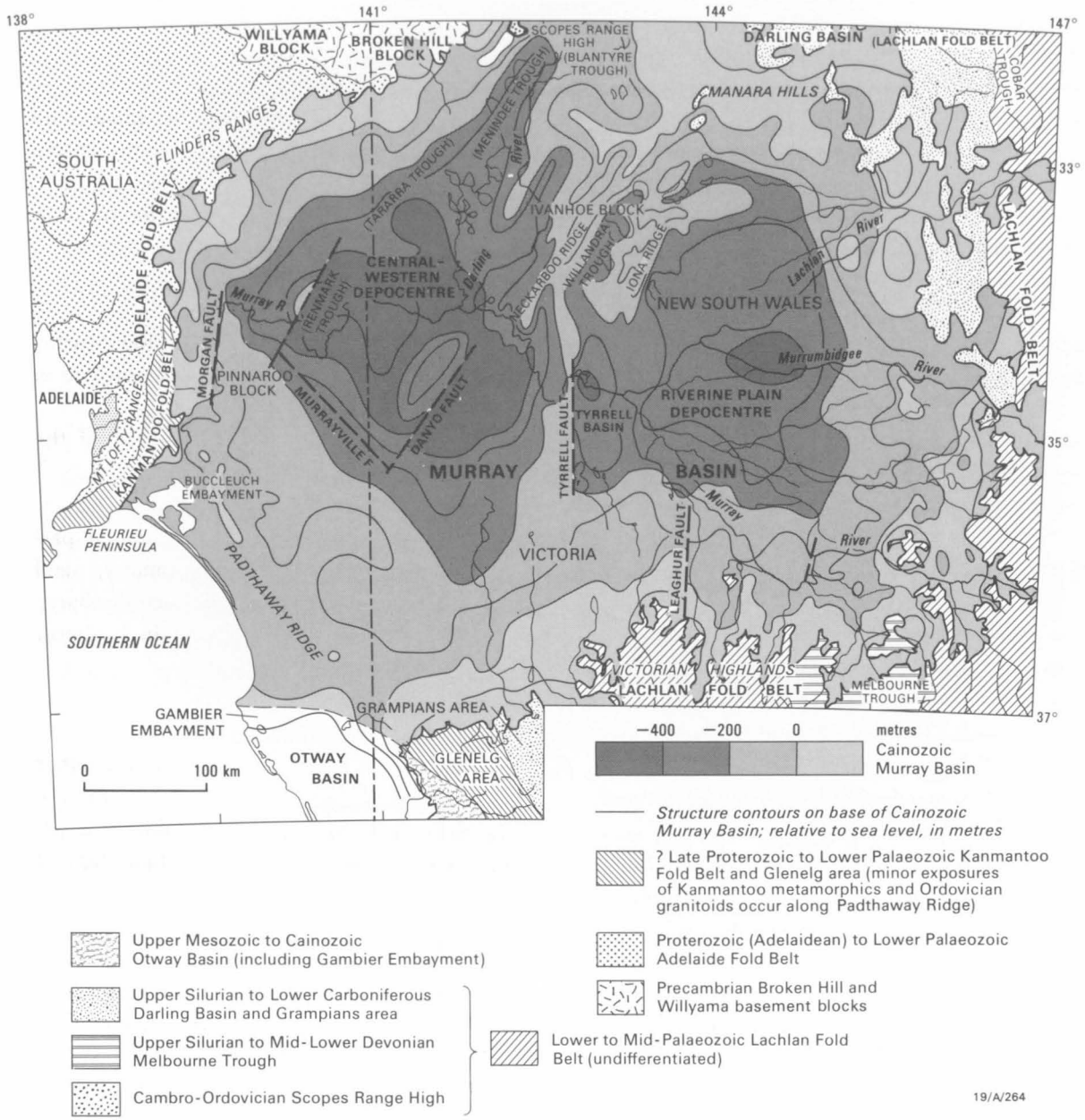


Fig. 4 . Tectonic framework of the Murray Basin, and base Cainozoic structure contours.

series of 1:2 500 000 scale Total Magnetic Intensity (TMI) pixel maps and a Bouguer gravity anomaly contour map, both produced by the Geophysical Observatories and Mapping Group, BMR (see Plates 15, 16, 17). Geophysical investigations in the basin are listed in Tables 40, 41, and 42. These include seismic, gravity, magnetic, and radiometric surveys undertaken by petroleum exploration companies, as well as by BMR and State organisations. The availability of geophysical maps is shown on Figure 7.

Economic geology. The main emphasis of the study has been on improving our understanding of the geological context of groundwater distribution and surface discharge in the Murray Basin, but at an early stage the scope of the study was expanded to include reference to other mineral resources. These include Cainozoic limestone, alluvial gold, kaolin, gypsum and halite deposits. Heavy mineral suites have been recorded in near-surface Pliocene sands, and are currently under investigation. The Tertiary succession also includes extensive deposits of brown coal, and is underlain by Upper Permian coal in the Oaklands Infrabasin in New South Wales. The Cainozoic Murray Basin is not prospective for hydrocarbons, but several concealed pre-Cainozoic infrabasins remain poorly investigated. Mineral occurrences are listed in Table 44.

Definition of terms. Most of the terms used in this Bulletin are defined in the American Geological Institute *Glossary of Geology* (Bates & Jackson, 1980). A variety of terrigenous and carbonate sedimentary rock classifications have been used in the past. There has been a tendency, for example, to classify the coarser-grained carbonate rocks according to grain-size (e.g. calcarenites) using the terms first used by Grabau (1903), whereas the finer-grained rocks (i.e. calcilutites) have often been classified according to the compositional scheme (e.g. micrite) of Folk (1959, 1968). In general, we have conformed to local convention, and retained the original lithologic descriptions given to the stratigraphic units, at the expense of consistency in sediment classification.

Definition of the Murray Basin

The Murray Basin is a low-lying saucer-shaped intracratonic basin containing thin flat-lying Cainozoic sediments, located in southeastern Australia between latitudes 32° and 37° south and longitudes 139° and 147° east (Fig. 2; Fenner, 1934). It extends approximately 850 km from east to west and 750 km from north to south and covers an area of 300 000 km^2 of western New South Wales, northwest Victoria, and southeast South Australia. The Cainozoic sediments unconformably overlie and onlap Proterozoic basement rocks of the Willyama and Broken Hill Blocks in the northwest, and Proterozoic and Lower Palaeozoic sedimentary and metasedimentary rocks of the Adelaide and Kanmantoo Fold Belts in the west (Fig. 4). These basement elements together form the subdued Mount Lofty and South Flinders Ranges, flanking the western margin of the basin. To the east, the basin overlies and is flanked by strongly folded and partly metamorphosed Ordovician to Devonian rocks of the Lachlan Fold Belt, which form the ranges of the eastern highlands. To the south, the basin onlaps folded and mildly deformed Cambrian to Lower Carboniferous rocks, also included in the Lachlan Fold Belt, and forming the Victorian highlands. To the north, the Cainozoic sequence overlies and onlaps low hills of folded Devonian to Lower Carboniferous sedimentary rocks of the Darling Basin (a younger component of the Lachlan Fold Belt). The southwest boundary of the groundwater basin is generally taken as the Padthaway Ridge – a lower Palaeozoic basement feature, almost entirely concealed by a thin condensed Cainozoic sequence. The Cainozoic succession of the Murray Basin extends across this basement feature, but it effectively forms a southern rim to the groundwater basin, and separates it from the thicker contiguous Cainozoic sequences of both the Southern Ocean and the Gambier Embayment of the adjacent Otway Basin. Descriptions of the Cainozoic stratigraphic units in the onshore area between the southwest flank of the Padthaway Ridge and the coast have been included in this Bulletin. In the north, the basin sediments are linked to the Cainozoic cover of the Great Artesian Basin via a narrow corridor of sediment beneath the Darling River flood plain (Darling Corridor of Devine & Power, 1970).

Beneath the Murray Basin, geophysical and borehole evidence suggests that the folded and partly metamorphosed Proterozoic and Lower Palaeozoic basement is block-faulted and that the Cainozoic sequence is locally underlain by poorly defined infrabasins preserved in graben-like troughs. These contain thick sequences of Devonian to Lower Carboniferous sediments and discontinuous, erosional remnants of Upper Carboniferous, Permian, Triassic and Cretaceous platform-cover sediments (see Fig. 23).

The Cainozoic succession of the Murray Basin forms an extensive blanket of sediment, with a maximum thickness of about 600 m preserved in the deeper, central-western parts of the basin (Fig. 4). A subsidiary depocentre with over 400 m of sediment underlies the central-west Riverine Plain, but in most northern, eastern, and southern parts of the basin the sediment succession is generally less than 200–300 m thick, and could be more accurately described as forming a thin platform-cover succession rather than a true basinal sequence. Within the Tertiary succession, at least three major depositional sequences (Paleocene–Eocene to Lower Oligocene, Oligocene–Middle Miocene, and Upper Miocene–Pliocene) have been identified (Brown, 1983, 1985). Each sequence consists of a package of genetically related formations separated by disconformities. Weakly lithified, non-marine, sand, silt, clay, and carbonaceous sedimentary rocks predominate in the east and north, but each of the depositional sequences includes marine sedimentary rocks in central and southwestern areas.

In the Mallee region of the west (Fig. 2), the Tertiary sedimentary rocks of the Murray Basin are almost entirely concealed beneath a mainly 'fossil' arid and semi-arid landscape of Quaternary aeolian dunefields, with minor fluvial and lacustrine morphostratigraphic units. Farther east, where the basin and adjacent highlands are drained by the Murray, Murrumbidgee and Lachlan Rivers, the Tertiary se-

quence underlies flat-lying fluvio-lacustrine and minor aeolian deposits of the semi-arid Riverine Plain.

Background to the Murray Basin hydrogeological project

In common with much of the Australian continent, the semi-arid Murray Basin is characterised by frequent periods of drought alternating with less-frequent periods of flood. The flow of surface waters in many of the river systems of the basin is often intermittent and unreliable. As a consequence, the Murray River and its tributaries have become highly regulated during the past hundred years of European development. In addition, extensive areas of the basin have become dependent on bore water for stock and human consumption, and locally for irrigation. The Murray Basin currently generates several billion dollars in annual agricultural income. Increased utilisation of the water resources of the basin over the past several decades has, however, led to the realisation that resources of good quality water are not unlimited. Both surface water and groundwater are extensively used by irrigators and graziers, and the future viability of many of the agricultural communities in the basin is increasingly dependent on the sustainable development and management of these water resources. Irrigation and clearance of natural vegetation in the Murray Basin have been accompanied by rising groundwater levels, resulting in increased land salinisation and discharge of saline water into river systems (e.g. Maunsell & Partners, 1979; Parliament of Victoria, 1984). In areas of dryland salinity, rising saline groundwater has resulted in formerly productive agricultural land being turned into marshy saline wasteland with dead trees (Fig. 1). Some irrigation areas, but particularly those in South Australia, are threatened by the increasing salinity of river water, while in other areas trees have been killed by waterlogging of their roots due to a rise in the groundwater table. In addition, the quality of drinking water in many towns and cities (including Adelaide), which depend on water from the Murray River, has deteriorated as a consequence of salinisation. The accelerated emergence of these salinity problems in recent decades has resulted in an urgent need to improve our understanding of the relationships between subsurface geology, aquifer geometry, recharge, groundwater flow and surface discharge as an aid to the management of the salinity problems of the basin.

Whilst there is much evidence of widespread salinisation of parts of the Murray Basin in the late Quaternary, it is now recognised that the European land management practices of the past 100 years have resulted in the re-activation of 'natural' systems within a fragile hydrologic regime. Consequently, the development of effective strategies to cope with salinity problems is of increasing concern to those communities in the basin which currently rely upon agriculture for their means of economic survival. Salts have accumulated at the surface of the basin due to evapotranspiration in areas where groundwater levels have risen to within the capillary zone. A major reason for the concentration of salts is that evaporation rates greatly exceed rates of rainfall, and saline groundwaters which have accumulated in the near-surface aquifers have not been flushed from the basin in recent geologic times. However, part of the problem also lies in current land use and water management policies.

At an early stage in the agricultural development of the Murray Basin it was realised that conservation of water resources was of considerable importance to sustained economic development, and the River Murray Agreement was adopted as early as 1917. The agreement was concerned, however, with only the regulation of the Murray River (Clarke, 1982), whereas the recent (1988) establishment of the Murray–Darling Basin Commission offers the opportunity for co-ordinated and co-operative management of the problems of the entire basin. There is now widespread public awareness of the problems of salinity-related land and river degradation (e.g. Cock & others, 1988). A major achievement of the Commission has been the rapid adoption of a basin-wide 'salinity and drainage strategy' by the Commonwealth and States (Murray–Darling Basin Ministerial Council, 1987a,b, 1988), in recognition of the serious nature of groundwater-related salinisation. The Murray Basin Hydrogeological Project was established against this background of increasing salinity problems, and has been incorporated into the work plan of the Groundwater Working Group of the Murray–Darling Basin Commission. The role of BMR has been to undertake basin-wide geological and hydrogeological studies, and, in particular, to compile a comprehensive document on the geology of the Murray Basin on behalf of the co-operating agencies.

Population, landuse and access

The Murray Basin and its tributary valleys support a population of approximately 2 million

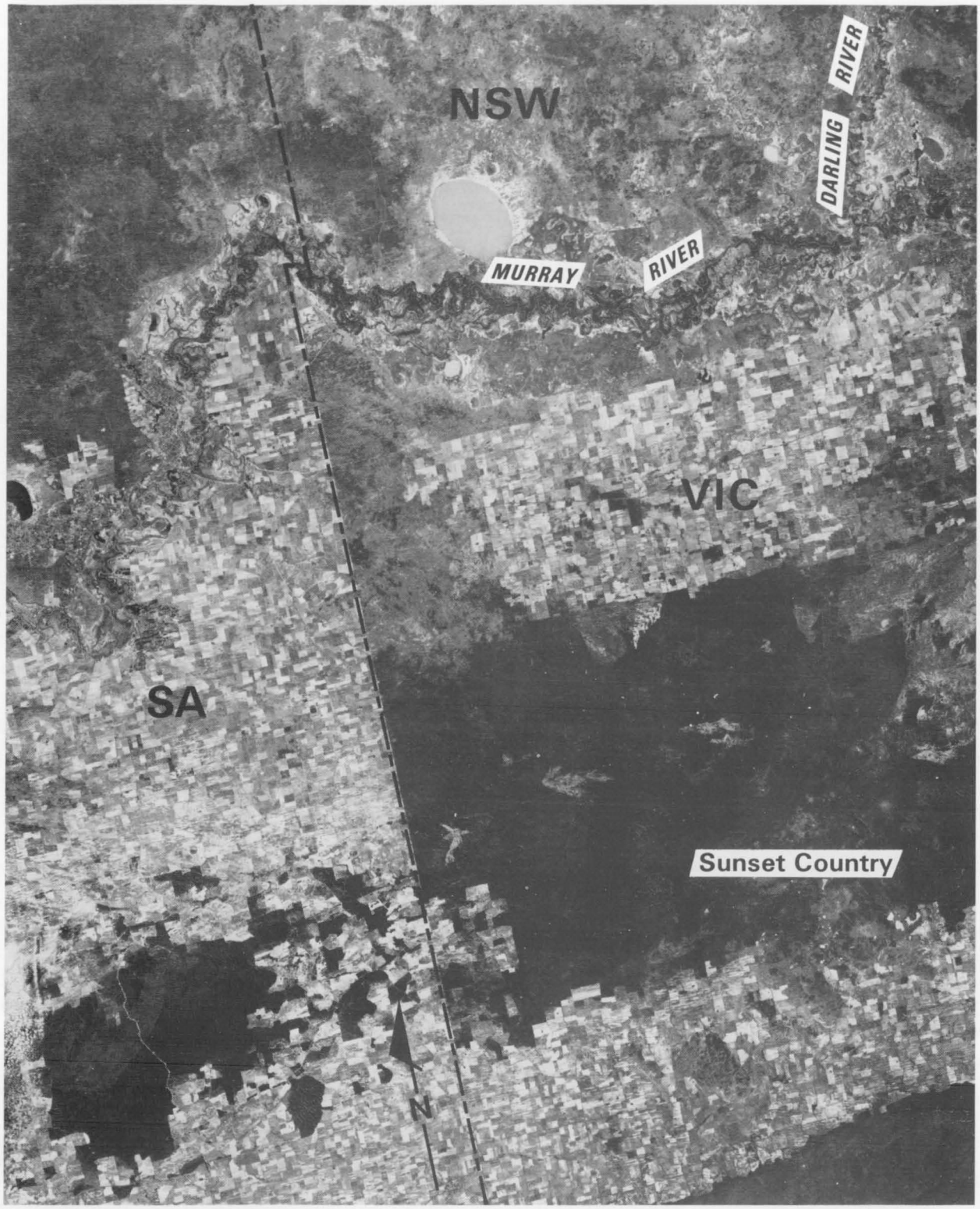


Fig. 5. LANDSAT–2 scene of tri-state border region – illustrating variations in land-use intensity across State borders; Renmark scene.

(Murray–Darling Basin Ministerial Council, 1987a). The largest population centres are located in the southeast Riverine Plain and adjacent highland areas. Further concentrations of population occur in the Riverina irrigation districts of the eastern Murray Basin in N.S.W., and along the course of the Murray River in South Australia. The wheat fields of western Victoria and southeast South Australia currently produce a large proportion of Australia's cereal grains. The western Riverine Plain and adjacent Mallee regions in New South Wales are amongst the most important wool-producing regions in Australia.

A Landsat scene of the tri-state border region (Fig. 5) illustrates variations in land-use intensity. In South Australia, irrigation schemes adjacent to the Murray River supply the nearby Adelaide market, and agricultural development of the South Australian part of the basin is intense, even in dunefield areas subject to erosion. Adjacent areas of Victoria are less cultivated, but wheat fields dominate the less-marginal lands. In contrast, farming in adjacent areas of western New South Wales to the north is less intense – reflecting increasingly arid climatic conditions, low population numbers, and remoteness from the state capital Sydney.

Irrigation schemes were first established in the Murray Basin in the late 1880's, and large schemes are now located at Renmark, Berri, Loxton, Waikerie, Mildura, Griffith–Leeton–Narrandera, and at several sites in the Riverine Plain of northern Victoria. In addition to the government supported schemes, which are serviced by networks of distribution canals, channels and drains, large areas are irrigated by landholders pumping water directly from the rivers. Some 3 million acres are now under irrigation. These produce large quantities of fresh, dried and canned fruits and vegetables to supply the major cities of southeastern Australia as well as export markets. They also produce grapes and support a number of important wine-producing centres. In the southeast Riverine Plain, extensive areas of irrigated pasture are used for the dairy industry, and production of associated milk products. Several large towns are highly dependent on water from the Murray River and its tributaries, and many originated as river ports, and evolved into service centres for local agricultural communities. South Australia is particularly dependent on water from the Murray River, which is piped to most of the urban centres in that State. Much of the economy of the region is therefore sensitive to the problems of land salinisation and increasingly saline river waters.

The agricultural and associated industries of the Murray Basin make a substantial contribution to the national economy of Australia. Because of this economic importance, several reviews of the resources and development of the basin have been undertaken over the past several decades (e.g. Department of National Development, 1947; Frith & Sawer, 1974; South Australian State Planning Authority, 1978). Reports, such as those by Gutteridge, Haskins & Davey (1970, 1983, 1985), Maunsell & Partners (1979), the Parliament of Victoria (1984), the Murray–Darling Basin Ministerial Council (1987a,b, 1988), Brown & Evans (1988), and Brown & others (1988), have emphasised the social and economic impact of increasing salinity problems in the Murray Basin. The Murray–Darling Basin Ministerial Council and Commission have been specifically established to develop strategies to overcome land and river degradation problems.

Access to most parts of the Murray Basin is excellent, with many towns and farming areas being well served by sealed highways and roads. The basin is located in Australia's populous southeast, with its margins being less than one hour by road from Adelaide, two hours from Melbourne, three hours from Canberra, and six hours from Sydney. Most locations are accessible by sealed all-weather roads, with the exception of areas north of the Murray River in western New South Wales and South Australia. These areas are sparsely populated, and access is by gravel roads which are infrequently made impassable at times of wet weather. The mobile dunefields of the Big, Little, and Sunset Deserts in Victoria have only limited access via vehicle tracks. In general, there are very few parts of the Murray Basin which are not accessible by conventional two-wheeled drive vehicles. The Murray Basin contains numerous towns, both large and small, as shown on the accompanying 1:1 000 000 scale map.

Topographic basemaps, at 1:100 000, covering southern and eastern areas of the basin have been published by the Australian Surveying and Land Information Group (AUSLIG), while 1:100 000 orthophotomaps of the western Murray Basin have been published by the New South Wales Central Mapping Authority. Publication of a series of 1:50 000 topographic maps of the Riverine Plain, also produced by the Central Mapping Authority in New South Wales, is nearing completion. Complete coverage of 1:250 000 topographic maps, originally published by the Royal Australian Survey Corps, has recently been updated and revised by the Australian Surveying and Land Information Group.

Acknowledgements

This study was undertaken in the Groundwater Branch, of the Minerals and Environment Group, BMR, and was issued first as BMR Record 1989/53 (Brown & Stephenson, 1989). The initial draft and accompanying geological map for the Record were edited by W.J. Perry. The Record was then prepared for the present Bulletin by Karl H. Wolf (BMR Editor). The authors thank both editors for their helpfull comments. Additional editorial comments were provided by S.R. Barnett, J.M. Lindsay and P.A. Rogers (South Australian Department of Mines and Energy), R. Brodie (BMR), C.R. Lawrence (Victorian Department of Water Resources), M. Reid and R. Thorne (Rural Water Commission of Victoria), D.R. Woolley and R.M. Williams (New South Wales Department of Water Resources).

The geological phase of the Murray Basin Hydrogeological Project was co-ordinated by the Groundwater Working Group of the Murray–Darling Basin Commission. At the time of completion of this Bulletin, the members of the Working Group were P.J. Cook (BMR, Chairman), S.R. Barnett (South Australian Department of Mines and Energy), D.J. Blackmore (Murray–Darling Basin Commission), R.S. Evans (Rural Water Commission of Victoria), W.R. Evans (BMR, Secretary), B. Harris (South Australian Engineering and Water Supply Department), C.R. Lawrence (Victorian Department of Water Resources), D.H. Probert (Geological Survey of New South Wales), and R.M. Williams (New South Wales Department of Water Resources). Past members include W.J. Perry (BMR) and D.R. Woolley (New South Wales Department of Water Resources).

The contribution of the members of the Groundwater Working Group, and other State personnel involved in the Murray Basin Project is gratefully acknowledged. In particular the sub-surface component of this study was partly compiled from borehole and stratigraphic material previously compiled by R.M. Williams (New South Wales Department of Water Resources), S.R. Barnett, D.R. Edwards, J.B. Firman, N.H. Ludbrook, E.D.P. O'Driscoll, and J.M. Lindsay (South Australian Department of Mines and Energy), C.R. Lawrence and P.G. Macumber (Victorian Department of Water Resources), S.J. Tickell and W.G. Humphrys (Geological Survey of Victoria), W.R. Evans and J. Kellett (BMR). The results of investigations undertaken by these colleagues in the participating State organisations have mainly been published in the various State Report Series, where much additional local detail is available. Data sources are listed in the accompanying text. Compilers of the previously published 1:250 000 geological maps used in the preparation of the accompanying 1:1 000 000 geological map are listed on the map face.

The co-operation of V. Anfiloff, A. Murray and D.H. Tucker of BMR, in production of the enclosed aeromagnetic imagery and Bouguer gravity contour map is gratefully acknowledged. The authors thank R.M. Featherston for the compilation of several text figures and tables, particularly those relating to soils, vegetation, climate and mineral occurrences.

The authors particularly thank Lindell Emerton, of the BMR Publications Drafting Group, who drafted the bulk of the figures. G.E. Butterworth and J. Convine of the Cartography Section BMR were responsible for initial drafting of the 1:1 000 000 map, and A.J. Maxwell completed the final drafting and cartographic edit. The authors also thank W.J. Perry for his support during the course of the study.

Fig. 6. Section across Murray River Gorge at Blanchetown (RENMARK), South Australia; published by Tate (1885 – his fig. 2).

PREVIOUS GEOLOGICAL INVESTIGATIONS

Evidence from the oldest known sites of human occupation in the Murray Basin suggests that the area was first colonised by aboriginal groups over 35 000 years ago (e.g. Bowler, 1976a). However, the Murray River was not discovered by European explorers until November 1824, when it was crossed by the Hume and Hovell expedition near the present-day site of Albury. Captain Charles Sturt (1833) subsequently recorded the first known geological observations in the basin when he examined the cliffs of the lower Murray River during his exploratory journey of 1830, following his expedition down the Murrumbidgee River in 1829. In 1836, Major Thomas Mitchell (1839) explored the Lachlan and Murrumbidgee Rivers and then travelled from the present-day site of Swan Hill across the southern margins of the basin. He reported favourably on the suitability of the land for pastoral development, resulting in a rapid influx of settlers. At a site adjacent to Greenhill Lake, near the Grampians Range in western Victoria, he also prepared the first geomorphic map of the crescentic transverse dune, now referred to as a lunette (Hills, 1940a; Bowler, 1983). By 1840, European exploration of the river systems of the Murray Basin was largely complete and most of the suitable pastoral land had been occupied.

The geology of both the concealed Tertiary succession and the Quaternary surficial cover of the Murray Basin has been intensively investigated over the past several decades, and an extensive body of geological knowledge has been generated. However, with the exception of the major publications of O'Driscoll (1960), Ludbrook (1961a) and Thornton (1974) in South Australia and Lawrence (1975) in Victoria, most of these geological data have been published in numerous short papers and reports widely distributed throughout the geological literature. Brief summaries of basin-wide geology are contained in Thornton (1976), Brown (1985, 1989) and Brown & Stephenson (1986), but no comprehensive, basin-wide documentation of the geology of the Murray Basin has previously been published. Only the major data sources used in the compilation of this Bulletin are referred to in the following section. Additional sources are listed in the accompanying References.

Groundwater investigations. The earlier knowledge of the concealed Tertiary geology of the basin has been generated largely by the necessity to exploit its groundwater resources, and the geological surveys and water authorities in each of the three States have undertaken extensive investigations of groundwater. Amongst the earliest investigations in Victoria was a report entitled 'Boring for Artesian Water in the Mallee', produced for the Water Supply Department by Jack & others (1897). A major review of borehole data and groundwater resources of northwest Victoria was published, 50 years later, by Gloe (1947) and followed by a comprehensive Memoir on the geology, hydrodynamics and hydrochemistry of the southern Murray Basin by Lawrence (1975). Further hydrogeological reviews on the Riverine Plain in northern Victoria have been produced by Tickell (1977a), Tickell & Humphrys (1980, 1987), and various aspects of the hydrogeology of the Loddon Valley and Mallee regions in Victoria published in a series of papers by Macumber (1966, 1968, 1969, 1973, 1978a,b,c, 1980, 1983, 1984a,b, in press), Collett (1978), and Teller & others (1982).

A survey of the underground water resources of the Murray Basin in South Australia by Barnes (1951), was followed by a comprehensive examination of borehole data and hydrology by O'Driscoll (1960), and reviews of groundwater adjacent to the River Murray by Cramsie (1969) and Roberts (1970a). Further recent assessments of the hydrogeology of the South Australian sector of the basin are to be found in a series of reports produced by the South Australian Department of Mines and Energy. These include reports by Reed (1980), Barnett (1980, 1981a,b, 1983, 1984, 1985, 1988a,b, 1989a,b), and Telfer (1989). The results of recent stratigraphic drilling programs have been documented by Edwards (1979, 1981a,b,c, 1982,a,b, 1983). Waterhouse & Gerges (1979) described the hydrogeology of the Angas–Bremer irrigation area near the coast in South Australia, and Waterhouse (1977) that of the Mount Gambier area of the adjacent Gambier Embayment.

Limited reviews of the hydrogeology of western and northern sections of the basin in New South Wales were undertaken by Kenny (1934), Mulholland (1940), and Gibbons & others (1972), and the hydrogeology of the Narrandera–Hay area of the Riverine Plain was summarised by Graillat (1971). The emphasis in these reviews was on water quality rather than geology. The only available hydrogeological review of the New South Wales sector of the basin is in a paper by Woolley & Williams (1978), and further hydrogeological aspects are described in reports and papers by Williamson (1969), Woolley & Kalf (1981), Drury (1982), Williams (1983a,b, 1985), Odins & others (1985), Gates (1986), New South Wales Department of Water Resources (1987), Gates & Williams (1988), and Kellett (1989).

A major basin-wide review of the hydrogeology of the Murray Basin has been recently published by Evans & Kellett (1989).

Tertiary geology. Early systematic stratigraphic studies of the Tertiary geology of the Murray Basin were undertaken by Tate (1878, 1885), who described the lithologies and fossil content of the Tertiary limestones of the 'Murravian Series' exposed in the Murray River Gorge in South Australia (Fig. 6). Tenison Woods (1860, 1867a) had earlier described and named the limestones at Mount Gambier in the Gambier Embayment to the south. Subsequent stratigraphic work has mainly been undertaken in conjunction with groundwater investigations. Descriptions and definitions of many of the major Tertiary stratigraphic units of the Murray Basin in South Australia have been published in a series of papers and reports by Ludbrook (1957, 1958a, 1961a, 1963a, 1969a, 1971). These South Australian reference sections are based partly on borehole data and partly on outcrop data from the Murray River Gorge. Additional descriptions of the Tertiary succession in South Australia are recorded in Howchin (1929), Harris (1966, 1985), Lindsay & Bonnett (1973), Lindsay & Williams (1977), Twidale & others (1978), Major (1986), and Lindsay & Barnett (1989).

In the Victorian sector of the Murray Basin, several of the concealed Tertiary stratigraphic units were initially described by Lawrence (1966, 1975). Additional data are given in Macumber (1969, 1978a,b,c, 1983), Abele (1976, 1988), Lawrence & Abele (1976, 1988), and Tickell & Humphrys (1979, 1980, 1987). Summaries of the concealed geology of the New South Wales sector of the basin are given in Pels (1969a), Bembrick (1974), Woolley (1978), and Woolley & Williams (1978). Additional lithologic descriptions are also recorded in numerous water, mineral, and petroleum exploration bore completion reports (Table 45) as well as in many micropalaeontological reports. Stratigraphic interpretations from 3000 boreholes are listed in Brown & Stephenson (1986).

Quaternary geology. The surficial Quaternary geology and complex morphostratigraphy of the basin have been extensively studied by geomorphologists, soil scientists and pre-historians, as well as by hydrogeologists and Quaternary geologists. Butler & others (1973) compiled a geomorphic map of the Riverine Plain, and Bowler & Magee (1978) published a geomorphic map with description of the semi-arid Mallee region of northern Victoria and western New South Wales. Summaries of the Quaternary geology of South Australia have been published by Firman (1967a,b, 1969a, 1973), and individual Upper Tertiary to Quaternary stratigraphic units in South Australia have been described and named in a series of papers and reports by Firman (1964, 1965a,b, 1966a,b,c, 1969b, 1971a,b, 1972). Lawrence (1966, 1975, 1976a, 1988a) described several Quaternary units in northern Victoria, based partly on re-definitions of soil-stratigraphic units, previously recognised by Butler (1958) in the Riverine Plain, and Churchward (1960, 1961, 1963a,b,c) in the Mallee dunefields. In the southwest, Ollier & Joyce (1986) identified regolith terrain units on the Hamilton 1:1 000 000 sheet.

The surface of the Murray Basin is characterised by a unique suite of fossil landforms which reflect the sensitivity of the landscape to climatic fluctuations of

the past several hundred thousand years. In particular, investigations of the sedimentology of various suites of salt and freshwater lake sediments and their associated lunette deposits (summarised in Bowler, 1983, 1986) have led to a greater understanding of the role of fluctuating groundwater levels in influencing the development of landforms associated with saline groundwater discharge. Other aspects of palaeohydrologic influence on landscape evolution are discussed in papers by Macumber (1966, 1968, 1970, 1977, 1978b,c, 1980, 1983, 1984a,b, in press).

Aspects of palaeoclimatic influence on the sedimentological character and geomorphic history of the Quaternary of southeastern Australia are summarised in Bowler (1971, 1976a,b, 1978a,b, 1981, 1982, 1988), Bowler & others (1976), and Bowler & Wasson (1984). Descriptions of geomorphic and sedimentological features of the Mallee dunefields and associated lacustrine deposits are recorded in papers by Hills (1939, 1940a,b, 1961, 1975), Stephens & Crocker (1946), Cane (1962), Blackburn (1962a,b), Rowan & Downes (1963), Gill (1966, 1973a), Lawrence (1966, 1975, 1980), McLaughlin (1966), Roberts (1968a), Bowler (1973, 1980), Bowler & Polach (1971), Bowler & Magee (1978), Rogers (1978, 1980a), Twidale & others (1978), Storrier & Stannard (1980), Teller & others (1982), Bowler & others (1986), Bowler & Teller (1986), and Luly & others (1986).

Geomorphic descriptions of both active and fossil fluvial channels of the Riverine Plain are given in Butler (1950, 1956, 1958, 1960), Langford-Smith (1960a,b, 1962, 1963), Pels (1964a,b, 1966, 1969a,b, 1970, 1971), Blackburn (1966a), Bowler (1966a,b, 1967, 1978a), Bowler & Harford (1966a,b), Schumm (1966, 1968a), Bowler & Macumber (1967, 1968), Currey & Dole (1978), Storrier & Kelly (1978), and Butler & others (1983).

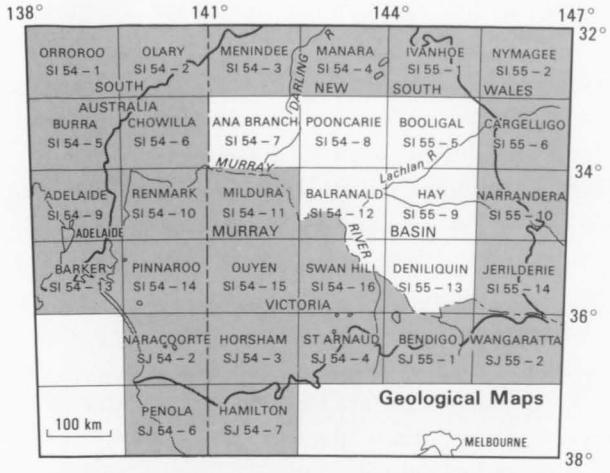
The Quaternary geology of coastal areas, with emphasis on the stranded beach complexes, has been described by Clarke (1896), Crocker & Cotton (1946), Hossfeld (1950), Sprigg (1952a,b, 1959, 1979), Blackburn & others (1965, 1967), Blackburn (1966b), Kenley (1971, 1976a, 1988a), Von der Borch (1965, 1976), Colwell (1976, 1978, 1979), Cook & others (1977), Von der Borch & Altmann (1979), Von der Borch & others (1980), Schwebel (1983, 1984), Tyler & others (1983), and Jenkin (1984).

Palaeontology and age determinations. Palaeontological investigations, commencing with those of Tenison Woods (1867b) and Tate (1878, 1885, 1889) have played a key role in elucidating the Tertiary stratigraphy of the basin, particularly in the marine succession of the western Murray Basin, where several of the stratigraphic units are essentially biostratigraphic in character. The early work of Chapman & Gabriel (1914), Chapman (1916, 1936), and Crespin (1946, 1947) provided detailed microfaunal listings from Oligocene to Pliocene sequences encountered in bores in the Victorian Mallee. Similar listings from borehole and river cliff sections in South Australia, and from petroleum wells throughout the basin, are recorded in a series of stratigraphic and micropalaeontological reports by Chapman (1943), Crespin (1953), Ludbrook (1956, 1957, 1958a,b, 1959, 1960, 1961a,b, 1962a,b,c, 1963a,b,c, 1964, 1965, 1967a, 1969a,b, 1971, 1973), Lindsay (1965a,b, 1966, 1967a,b, 1972, 1982a,b,c, 1983a,b, 1985a, 1987), Ludbrook & Lindsay (1966, 1969), Lindsay & Bonnett (1973), Lindsay & Giles (1973), and Lindsay & Williams (1977). A number of additional palaeontological papers documenting faunal assemblages from the Murray Basin region are included in a recent special publication of the Mines Department of South Australia, edited by Lindsay (1985b).

The palynology of Tertiary sediments from boreholes in western areas has been described in reports by Evans & Hodgson (1963), Harris (1963, 1964, 1965, 1970, 1971, 1973, 1985), Kress & others (1978), Archer (1984), Truswell & others (1985), McMinn (1986a), Macphail (1987, 1988a,b), Macphail & Truswell (1988, 1989), and Martin (1988, 1989). Harris & Morgan (1976), Martin (1973, 1977, 1984a,b,c, 1986a,b, 1987, 1989), McMinn (1981), Truswell (1987), and Knight & Martin (1989) have listed palynological assemblages and age determinations from the non-marine Cainozoic succession beneath the Riverine Plain in the east. The palynology of Cretaceous sediments beneath the Murray Basin has been summarised by Evans & Hawkins (1967). Additional Permian, Triassic and Cretaceous floras, including material from the Oaklands Basin, are listed in Evans (1962, 1963, 1967a), Morgan (1975a,b, 1976a,b, 1977a,b), and McMinn (1981, 1986a,b).

Radiometric and palaeomagnetic techniques have proved particularly useful in documenting the chronology of the complex Quaternary sedimentation patterns of the basin, as well as in reconstructing palaeoclimatic and depositional environments (e.g. Bowler, 1980; An Zhi-Sheng & others, 1986). Reports with fossil, radiometric, and magnetic age determinations are tabulated in Appendix 4.

Biostratigraphic schemes. Local chronostratigraphic stage names for the Tertiary marine stratigraphic sequences of southeastern Australia, based on fossil



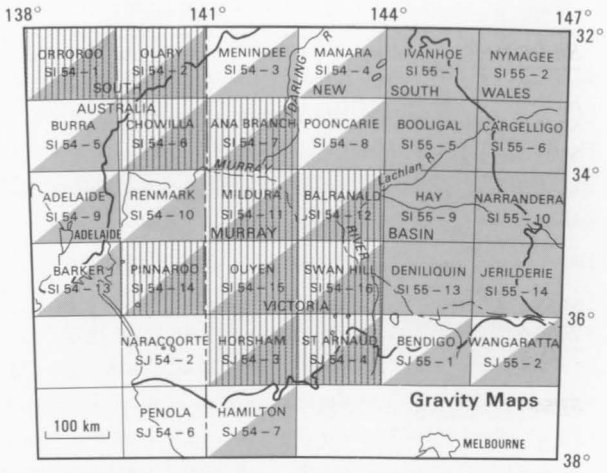
1:250,000 scale geological map published (References on accompanying Table)

Additional Geological Maps:—

NSW: 1:1 000 000 Geology of NSW (Pogson, 1972)
1:1 000 000 Tectonic map of NSW (Scheibner, 1974)
1:50 000 Geological Sheets — WENTWORTH (Cameron and Goldberry, 1971), URANA (Offenberg, 1972)
LACHLAN (Goldberry and West, 1977)

SA: 1:1 000 000 Geology of SA (Thompson, 1980)
1:500 000 Geology of south east SA (Rogers, 1980b)

VIC: 1:1 000 000 Geology of VIC (Geological Survey of Victoria, 1977)



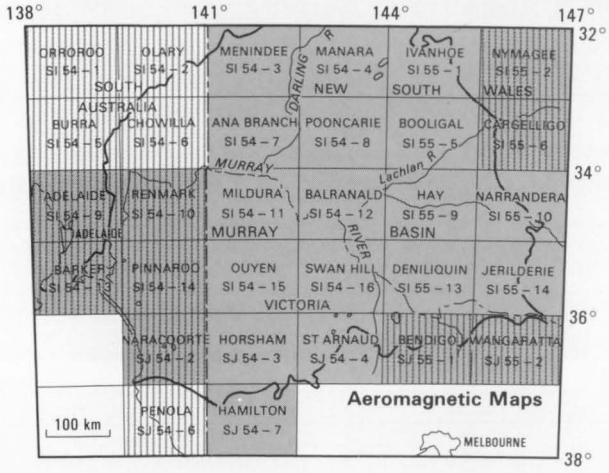
Pre-1981 Bouguer anomaly contour maps at 1:500 000 scale (reduced from 1:250 000)

Computer generated dyelines at 1:250 000 scale

Published

In progress

Dyelines available from Copy Service, BMR, CANBERRA, ACT 2601.

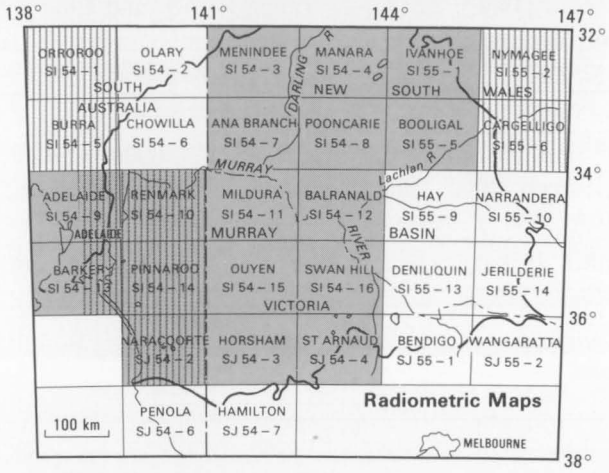


Pre-1970 total magnetic intensity contour maps at 1:250 000 scale

Dyelines at 1:250 000 scale (post-1970)

Pre-1970 maps available from BMR; South Australian maps available from SA Department of Mines and Energy.

Dyelines available from Copy Service, BMR, CANBERRA, ACT 2601.



Pre-1970 radiometric contour and/or spot anomaly maps at 1:250 000 scale

Dyelines at 1:250 000 scale (post-1970)

Pre-1970 maps available from BMR; South Australian maps available from SA Department of Mines and Energy.

Dyelines available from Copy Service, BMR, CANBERRA, ACT 2601.

19/A/267

Fig. 7. Index to 1:250 000 map sheet areas in Murray Basin, showing availability of geological and geophysical maps.

TABLE 1. PUBLISHED 1:250 000 GEOLOGICAL MAPS

Sheet No.	*Name*	*Year*	*Compiler(s)*	*Reference/Explanatory Notes*
SI/54-9	ADELAIDE	1969	Thomson, B.P.	Thomson (1969a)
SI/54-7	ANABRANCH	–	not yet published	–
SI/54-12	BALRANALD	1974	Lawrence, C.R. (Vic.)	Lawrence (1974a)
		–	N.S.W. part not yet published	–
SI/54-13	BARKER	1962	Thomson, B.P., & Horowitz, R.C.	Thomson & Horowitz (1962)
SJ/55-1	BENDIGO	1975	King, R.L., & Wilkinson, H.E.	Wilkinson (1977)
SI/55-5	BOOLIGAL	–	not yet published	–
SI/54-5	BURRA	1964	Mirams, R.C.	Mirams (1964)
SI/55-6	CARGELLIGO	1967	Pogson, D.J.	Pogson (1967)
SI/54-6	CHOWILLA	1977	Rogers, P.A.	Rogers (1978)
SI/55-13	DENILIQUIN	1974	Lawrence, C.R, (Vic.)	Lawrence (1974a)
		–	N.S.W. part not yet published	–
SJ/54-7	HAMILTON	1971	Douglas, J.G., & Spencer-Jones, D.	Mines Department of Victoria (1971)
SI/55-9	HAY	–	not yet published	–
SJ/54-3	HORSHAM	1974	Lawrence, C.R.	Mines Department of Victoria (1974a)
SI/55-1	IVANHOE	1968	Bryan, J.H.	Bryan (1968)
SI/55-14	JERILDERIE	1969	Tuckwell, K.D.	Tuckwell (1969)
SI/54-4	MANARA	1966	Bryan, J.H.	Bryan (1966)
SI/54-3	MENINDEE	1967	Rose, G.	Rose (1967)
SI/54-11	MILDURA	1972	Lawrence, C.R.	Mines Department of Victoria (1972) & Lawrence & Goldberry (1973)
SJ/54-2	NARACOORTE	1969	Rochow, K.A.	Rochow (1969)
SI/55-10	NARRANDERA	1974	Pogson, D.J.	Wynn (1962) & Pogson (1974)
SI/55-2	NYMAGEE	1968	Brunker, R.L.	Brunker (1973)
SI/54-2	OLARY (Prelim)	1976	Forbes, B.G.	Forbes (1976) & Forbes & Pitt (1980)
SI/54-1	ORRORO	1968	Binks, P.J.	Binks (1968)
SI/54-15	OUYEN	1973	Lawrence, C.R.	Lawrence (1974b)
SJ/54-6	PENOLA	1951	Sprigg, R.C., Cochrane, G.W., & Solomon, M.	Sprigg & others (1951)
SI/54-14	PINNAROO	1980	Rogers, P.A.	Rogers (1980a)
SI/54-8	POONCARIE	in press	Cameron, R.G.	–
SI/54-10	RENMARK	1971	Firman, J.B.	Firman (1972)
SJ/54-4	ST. ARNAUD	1976	King, R.L., Wilkinson, H.E., & Macumber, P.G.	King (1977)
SI/54-16	SWAN HILL	1974	Lawrence, C.R.	Lawrence (1974c)
SJ/55-2	WANGARATTA	1974	Lawrence, C.R., & Joplin, G.A.	Mines Department of Victoria (1974b) & Laing & others (1977)

assemblages, were proposed by Hall & Pritchard (1902) and modified, redefined, or added to by Singleton (1941), Crespin (1943), Ludbrook & Lindsay (1966), Ludbrook (1973), and Lindsay (1985a). As discussed by Abele (1976, 1988), a number of biostratigraphic schemes, largely defined by the distribution of local foraminiferal assemblages, were subsequently developed in southeastern Australia (e.g. Glaessner, 1951; Carter, 1958a,b; Jenkins, 1960; Wade, 1964; Ludbrook & Lindsay, 1969; McGowran & others, 1971; McGowran, 1973). Correlations between the local assemblages and the international time-scale, as discussed by Abele (1976, 1988), are published in McGowran & others (1971), and McGowran (1978a,b, 1979). Regional and local correlations between foraminiferal assemblages and eustatic relative coastal onlap curves of Vail & Mitchum (1979) are given in Loutit & Kennett (1981), and Lindsay (1983a, 1985a). Correlations between the stratigraphy of the basin and the coastal onlap curves are discussed in Brown (1983, 1985).

Harris (1965, 1971, 1985) recognised several spore–pollen zones in the Tertiary of southeastern Australia, particularly in the coastal sediments of the Gambier Embayment in South Australia. An alternative Tertiary palynological zonal scheme was developed for the Gippsland Basin by Partridge (1971), Stover & Evans (1973), and Stover & Partridge (1973), and has found limited application in the non-marine succession of the southeastern Murray Basin. The scheme has been used as a correlation standard, but is less readily applicable in other areas of the Murray Basin where the palynological assemblages are substantially different from those of the Gippsland Basin – thus preventing satisfactory correlations with the southeastern Australian scheme. As part of a program aimed at resolving this deficiency, Truswell & others (1985) established a palynological reference column for Oligocene–Miocene sediments in the SADME Oakvale No.1 borehole, located in the northwestern part of the basin. The reference column was calibrated by means of foraminiferal age deter-

minations from Lindsay (1983a).

Pre-Cainozoic infrabasins. The geology of the deeper parts of the Murray Basin and underlying Devonian, Permian, Triassic and Cretaceous infrabasins has been derived largely from petroleum wells and mineral exploration bores. Petroleum exploration activity has been summarised by the Bureau of Mineral Resources (1964), Thornton (1974, 1976), Bembrick (1974), Evans (1977), Brown & others (1982), Byrnes (1985), and Sniffen (1985). Petroleum exploration well-completion reports, in addition to reports on deep stratigraphic bores, are listed in Table 45. The geology of the underlying Cretaceous has been reviewed by Evans & Hawkins (1967), and the Permian and Triassic sedimentary rocks have been described by Palese (1974), Morgan (1977a), and O'Brien (1981, 1986).

Basement geology and geophysical investigations. The configuration of shallow basement features and infrabasins concealed beneath the Murray Basin has been defined mainly by numerous geophysical surveys undertaken by petroleum exploration companies and by the Bureau of Mineral Resources. Most surveys were conducted during the period 1960–1970 and were concentrated mainly over the more prospective infrabasins underlying the western Murray Basin in New South Wales and South Australia. A history of geophysical investigations in South Australia during this period is documented in Seedsman (1964a) and Thornton (1974). Similar histories of geophysical investigation in western New South Wales are documented in Bauer & others (1979), Byrnes (1985), and Sniffen (1985).

Most seismic reflection surveys completed during the 1960–1970 period of exploration, produced poor-quality results. However, subsequent surveys by Beaver Exploration (1973), and more recently by Comserv (1981a,b,c,d, 1982a), BHP Petroleum (1983) and Esso Exploration (1983), have obtained high-quality profiles. Seismic surveys were also conducted during the course of investigation of the Upper Permian coal deposits in the Oaklands Basin beneath the southeastern Murray Basin (Thyer & Vale, 1952; summarised by McIntyre, 1976). These have been supplemented by recent high-quality reflection profiles obtained by Palmer (1977) and Meekatharra Minerals (1983). Additional refraction seismic surveys have also been undertaken in key areas by the New South Wales Department of Water Resources. These have been used to define the geometry of Tertiary aquifers and to locate the presence of shallow basement features (e.g. Odins & others, 1985; Odins, 1987a,b). Regional Bouguer gravity anomaly maps have been compiled by Anfiloff & others (1976) and the Bureau of Mineral Resources (1976). Several gravity-defined highs and lows were identified in Bembrick (1974), Thornton (1976), and Brown & others (1982). With the exception of some western, southern and eastern areas, almost the entire basin has been covered by digital aeromagnetic surveys, the results of which have been published by BMR at 1:250 000 scale (Fig. 7). More recently the digital dataset has been used to generate total magnetic intensity imagery of standard 1:1 000 000 Sheet areas within the Murray Basin region, and these have been combined to form a single total magnetic intensity pixel map (Tucker & others, 1985a,b), presented in grey-scaled and colour-scaled forms (Plates 16, 17). A regional interpretation of the geological sources of magnetic and gravity anomaly fields in areas of the Lachlan Fold Belt, adjacent to the eastern margin of the Murray Basin is presented in Wyatt & others (1980), and the aeromagnetic character of basement beneath the northwestern Murray Basin is discussed by Tucker (1983). A preliminary interpretation of magnetic domains beneath the Murray basin is presented in Brown & others (1988).

The coverage of aeromagnetic, radiometric and gravity maps in the Murray basin is shown in Figure 7.

Economic geology. A general description of the resources of the South Australian part of the basin is given in Johns (1969) and detailed descriptions of individual mineral occurrences are recorded in a number of papers in the annual Mineral Resources Review series, published by the South Australian Department of Mines and Energy. The mineral occurrences of the Victorian part of the basin are reviewed in a number of short articles in Douglas & Ferguson (1976, 1988). Summaries of the mineral resources in the New South Wales part of the basin are given in Bembrick (1974; in Markham & Basden, 1974). Mineral exploration activity in the basin is monitored by the Mines Department in each State, each of which also maintains an open-file archival retrieval system, storing numerous unpublished mineral and petroleum exploration reports. The more significant of these, as well as surveys undertaken by government agencies, are referred to in the appropriate sections of Chapter 15.

Geological mapping. Geological maps of the basin have been compiled at 1:250 000 scale by the relevant State geological surveys for each of the thirty Sheets covering the Murray Basin, with the exception of six Sheets in western New South Wales. Each State geological survey has also published 1:1 000 000

geological maps, which include the appropriate portions of the Murray Basin. In addition, the geology of the New South Wales part of the basin was included in a series of maps at 1:500 000. A preliminary edition of the enclosed 1:1 000 000 geological map was produced in 1985 (Brown & Stephenson, 1985). The availability of geological maps in the Murray Basin is documented in Figure 7 and Table 1. Detailed geological maps have not generally been produced, although a number of small-scale maps covering the southern margins of the basin (where they merge with the northern margins of the Otway Basin) are included as Enclosures in Wopfner & Douglas (1971).

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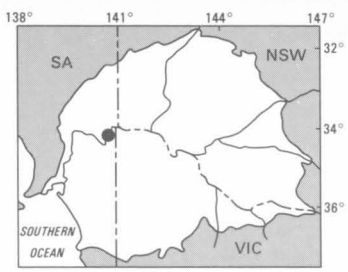

Fig. 8. Loxton–Parilla Sands (under Blanchetown Clay and Woorinen Formation) forming cliffs of Murray River Gorge, notheast of Renmark.

PHYSIOGRAPHIC SETTING

Topography and drainage patterns

The low-lying Murray Basin extends over 300 000 km^2 of inland southeast Australia (Fig. 2; Plate 2). The margins of the basin onlap the flanking ranges to an elevation, which only locally exceeds 200 m above sea level (m.a.s.l.). The basin surface is relatively flat, but dips gently down from its margins to the lowest-lying areas in the central-west. Some lake floors in this area are only 20 m.a.s.l. The origin of a rim along the southwestern margins of the basin can be related to uplift of concealed basement features of the Pinnaroo Block and the coastal Padthaway Ridge (Fig. 4), where Ordovician granites crop out as local topographic highs. This uplift of the southwestern margin has resulted in separation of the groundwater basin from the Southern Ocean, and has also resulted in internal drainage patterns, which focus on the topographically depressed central-western area. The Murray River manages to escape to the sea from this low-lying area only via a gorge incised into elevated Tertiary sediments of the Pinnaroo Block and Padthaway Ridge.

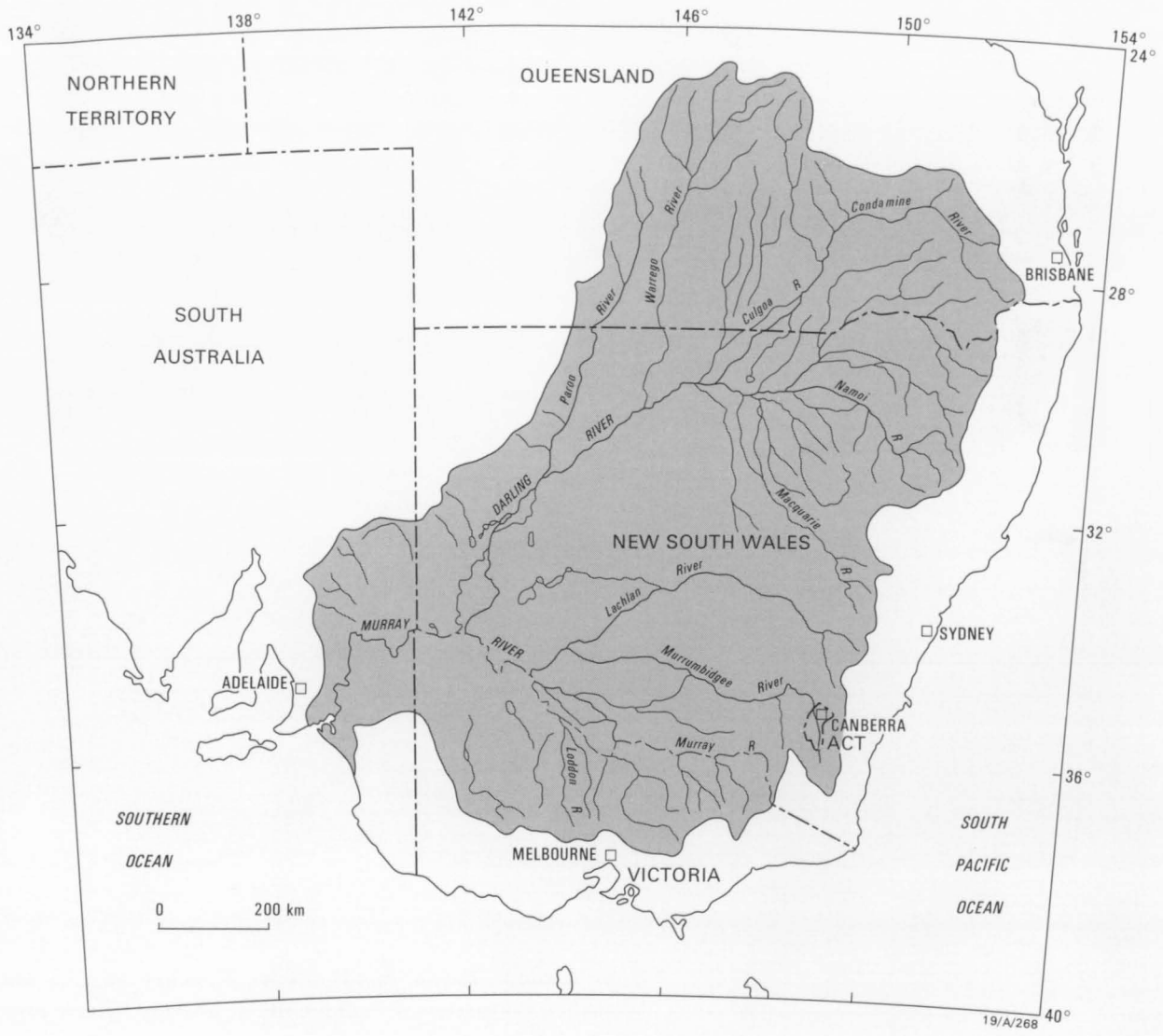

Fig. 9. Murray–Darling drainage basin, southeastern Australia.

The Murray–Darling drainage basin forms the single largest co-ordinated river system in the Australian continent (Fig. 9), occupying an area of 1 036 000 km^2 (Hills, 1974). It includes almost the entire Murray sedimentary basin, with the exception of a small area at the southern margin which drains to the Glenelg River to the south. The dominant river, the Murray, is 2570 km long and for 2200 km of its course flows within the Murray basin. The headwaters of the river are located in the Snowy Mountains and drain the inland slopes of the southeastern highlands. Its major tributaries, the Murrumbidgee and Lachlan Rivers, drain central and southern parts of inland New South Wales, and the Ovens, Goulburn, Campaspe, Loddon and Avoca drain the northern Victorian Highlands. Before entering the Murray Basin, the Darling River (2730 km long) and its tributaries drain an extensive area of inland northern New South Wales and southeastern Queensland. The rivers of the Murray–Darling system are generally meandering and slow-flowing on the low gradients of the inland plains, with anabranching not uncommon. The term 'anabranch' of Jackson (1834) is thought to be a corruption of 'anastomosing branches' (Gill, 1973a). In the northern Murray Basin, near Menindee, the Darling Anabranch splits off from the Darling River and pursues its own course to the south, where it flows into the Murray River 14.5 km downstream from the confluence of the Murray and Darling Rivers at Wentworth, 820 km upstream from the sea. The Murray River flows into the Southern Ocean via Lake Alexandrina, and is the only major river to reach the sea from the Murray Basin.

Despite its large catchment, the Murray–Darling system, the fourth longest in the world, is certainly not amongst the world's largest river systems in terms of volume of water carried, with an average runoff equivalent to only 2 cm of rainfall per annum over the whole catchment (Hills, 1974). With

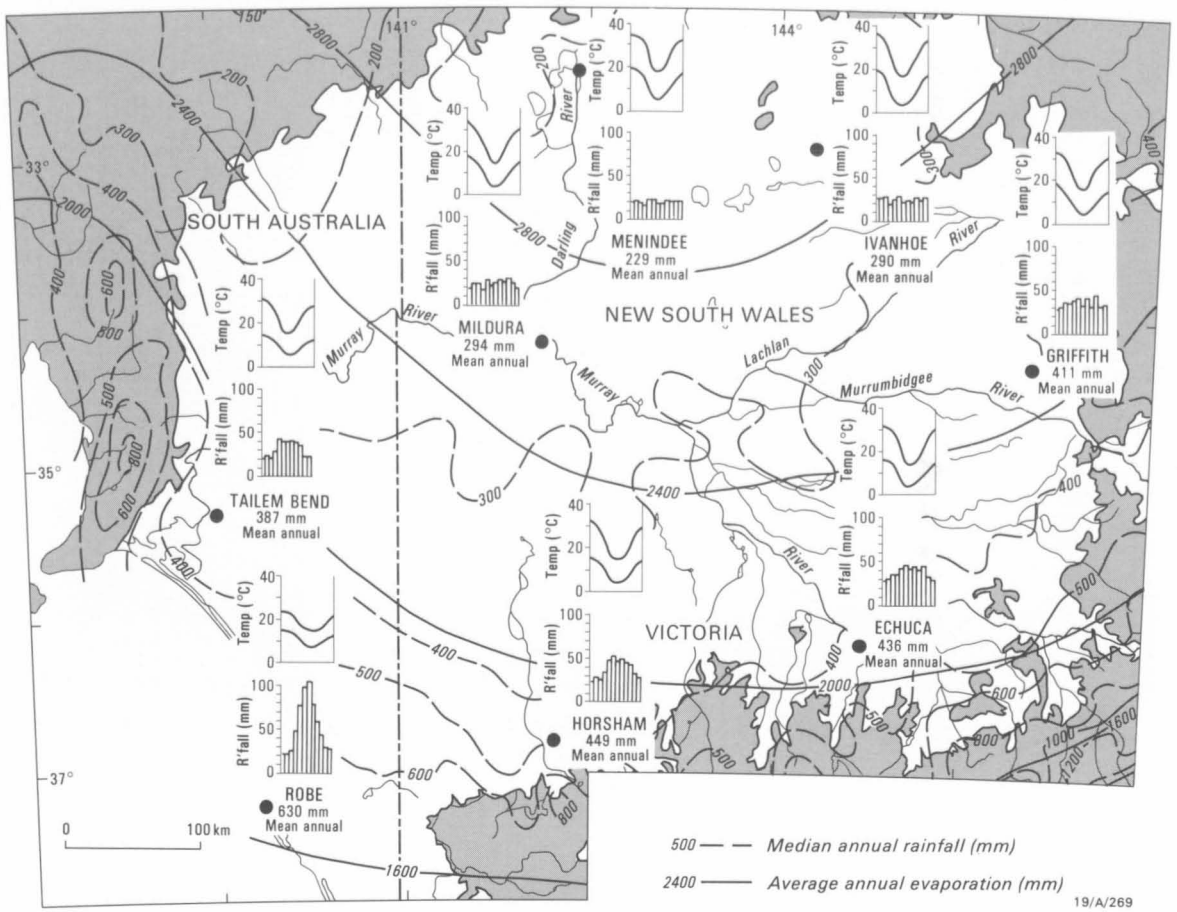

Fig. 10. Climate of the Murray Basin – annual rainfall and evaporation contours; monthly rainfall and temperature histograms for selected sites (from Bureau of Meteorology, 1975 – *Climatic Atlas of Australia*, Map Sets 3 and 5).

the exception of the southeastern highlands, most of the drainage basin has low annual run-off, averaging only 15 000 m^3/km^2 (Gill, 1973a). Flows within the Darling system are particularly variable – the Darling itself has ceased to flow in some dry years, and its water contribution to the Murray–Darling system is relatively small. Because this entire river system is frequently affected by periods of drought or flood, present-day river flows are artificially maintained for navigation and irrigation by a series of locks and barrages. This has considerably reduced flow variability since the late 1920's (Baker & Wright, 1978). Water allocation rights are determined by the Murray–Darling Basin Commission in consultation with relevant state water authorities.

For most of their courses, the Murray and Darling Rivers, and their major tributaries are typical exotic rivers, receiving very little water from within the basin. In the aeolian landscapes of the western Murray Basin, virtually no surface run-off reaches the Murray River, and the Darling River and its Anabranch are its only permanently flowing tributaries. Ephemeral streams entering the sedimentary basin from the ranges at its northern and northwestern margins tend to dissipate within aeolian plains. In the Mallee dunefields in the west, small claypans and salinas between the dunes serve as local drainage sumps after intermittent rain.

Climate – rainfall and evaporation

Most of the Murray Basin can be regarded as semi-arid, although the basin experiences a range of climatic conditions. In southern areas, most rain falls in winter when a succession of cold fronts and low-pressure systems sweep across the basin from the west. Precipitation is less seasonably reliable in northwestern areas, where summer thunderstorms bring most of the rain. Remnants of tropical depressions also occasionally travel sufficiently far south to contribute to summer rain in the basin. Median annual rainfall and annual evaporation over the basin are shown in Figure 10, which also shows average monthly rainfall and temperatures for selected localities. Mean annual evaporation for the Murray Basin is high (Fig. 10), and the trend is that as rain-

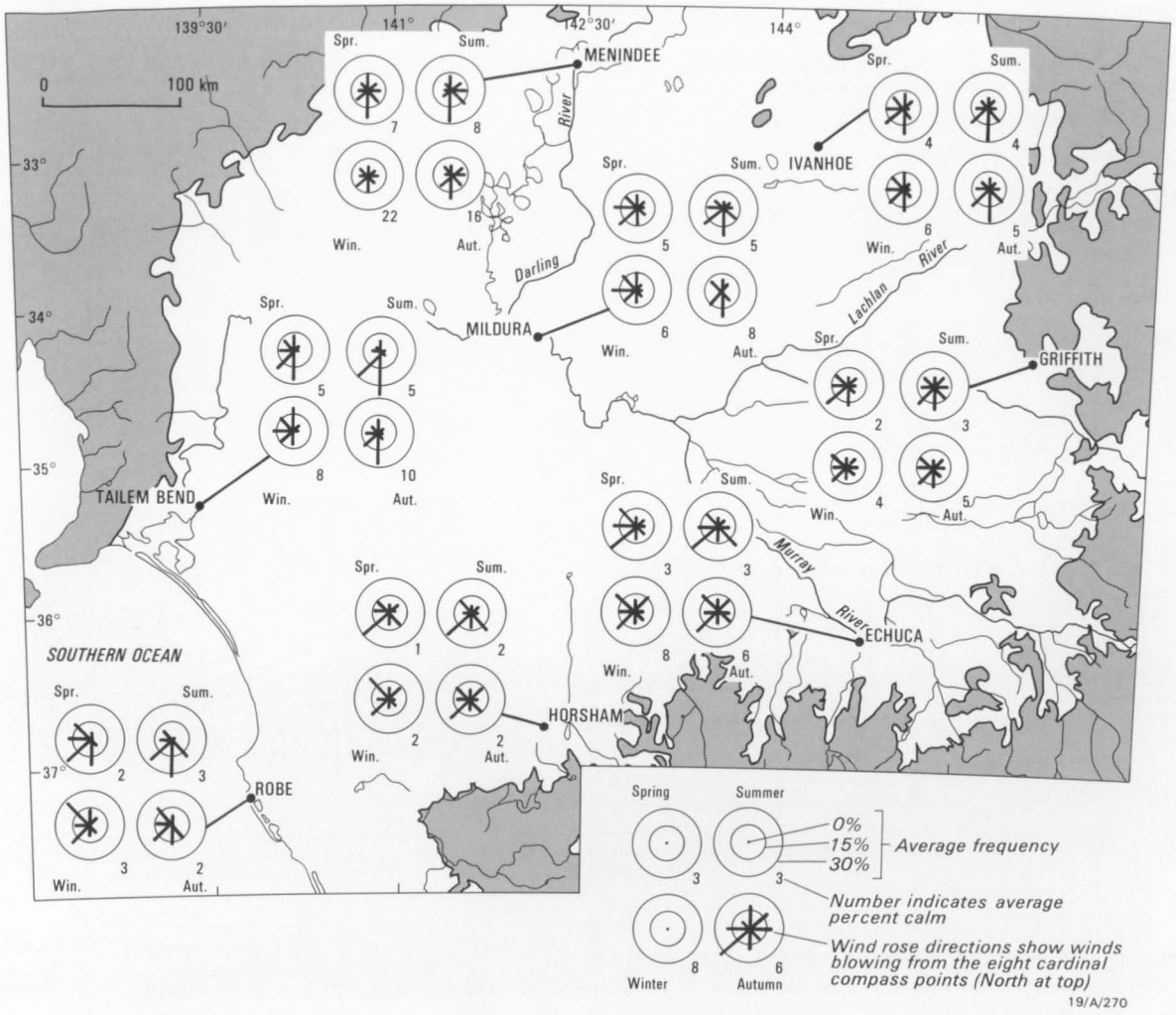

Fig. 11. Seasonal average frequency of direction of surface winds at selected sites in the Murray Basin (from daily readings at 3.00 p.m., except for Menindee which was read at 9.00 a.m.

fall decreases the evaporation increases, although evaporation rates are not modified by the presence of the flanking ranges to the same extent as is rainfall. Evaporation rates significantly exceed rainfall throughout the basin, so that the Murray–Darling river system (Fig. 9) is dependent upon precipitation falling outside the Murray sedimentary basin for most of its water intake.

The dominant year-round wind directions are from the west and south; these have strongly influenced the pattern of aeolian dune development and migration in the Murray Basin. Seasonal variations in surface wind directions in the basin are shown in Figure 11.

Vegetation

The Murray Basin supports several different vegetation assemblages, reflecting various permutations of geology, soil type, drainage pattern, climate, and in many areas the activities of man (Fig. 12). No region of the Murray Basin is extensively vegetated by tall trees (Carnahan, 1976), and much of the original native vegetation has been cleared (Murray–Darling Basin Ministerial Council, 1987a). Isolated stands of tall eucalypts (Red Gums) grow along the course of the Murray and other rivers (for example Barmah Forest; see Fig. 16). Medium trees (10–30 m high) only form forests in the area of highest rainfall adjacent to the southern and eastern margins of the basin; low trees (<10 m high) occur in an area of lower rainfall in the north of the basin. A large part of the Riverine Plain is vegetated by low trees and tussock grasses – however, there is also an extensive grass-covered area within the Riverine Plain, known as the Hay Plains (see Fig. 14), where the tallest shrubs are less than two metres high (Z3-4 on Fig. 12; Carnahan, 1976). The Mallee region is

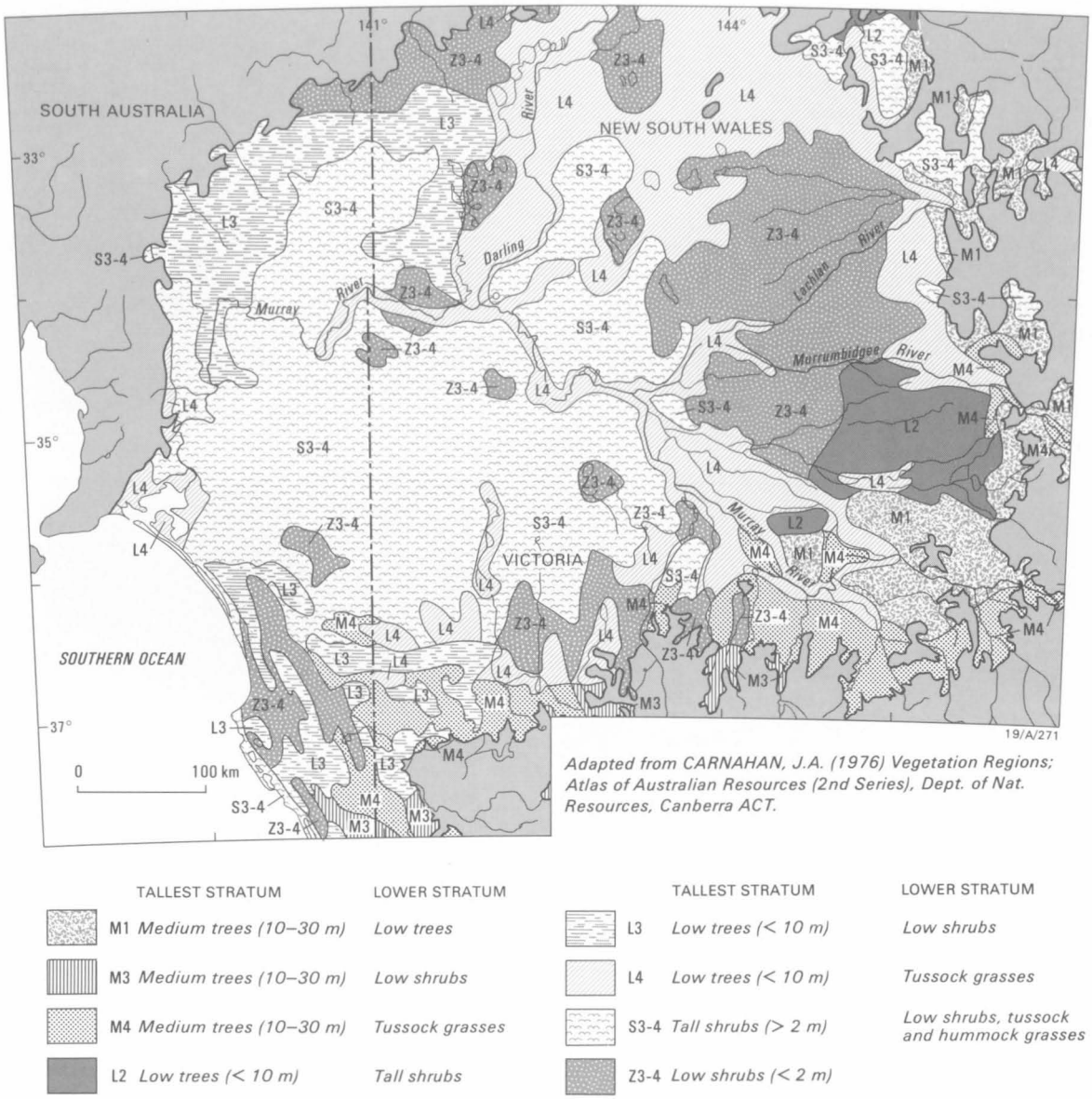

Fig. 12. Vegetation regions of Murray Basin – adapted from Carnahan (1976) – *Vegetation Regions, Atlas of Australian Resources* (2nd Series), Department of National Development, Canberra.

also relatively treeless, but tall woody, tree-like shrubs ('Mallee' of the genus *Eucalyptus*) characterise the aeolian dunefields (Noble & Mulham, 1980). Within the Mallee region, the valleys of the Murray River, Darling River, and Darling Anabranch are comparatively well vegetated with dense stands of trees and shrubs.

The activities of man have extensively modified the vegetation of the Murray Basin. Large areas in the southern half of the basin have now been cleared for wheat and other grain cultivation, as well as extensive northern areas for grazing. In addition, there are major irrigation areas adjacent to the Murray, Murrumbidgee, and Lachlan Rivers, which have been cleared for orchards, vineyards, rice fields, and other cultivation. Overstocking of the land with sheep has caused degradation of the natural vegetation, particularly in some areas of western New South Wales.

Soils

The Murray Basin has at least twelve major soil types (Fig. 13), as well as calcareous sand at the coast. These soil types can be closely related to the underlying Quaternary geology. Grey and brown soils of the Riverine Plain and Murray–Darling River valleys (D2), and solonized brown soils of the Mallee region and some basin margins (D1) cover by far the largest areas. The grey and brown soils overlie mainly the fluvial Shepparton and Coonambidgal Forma-

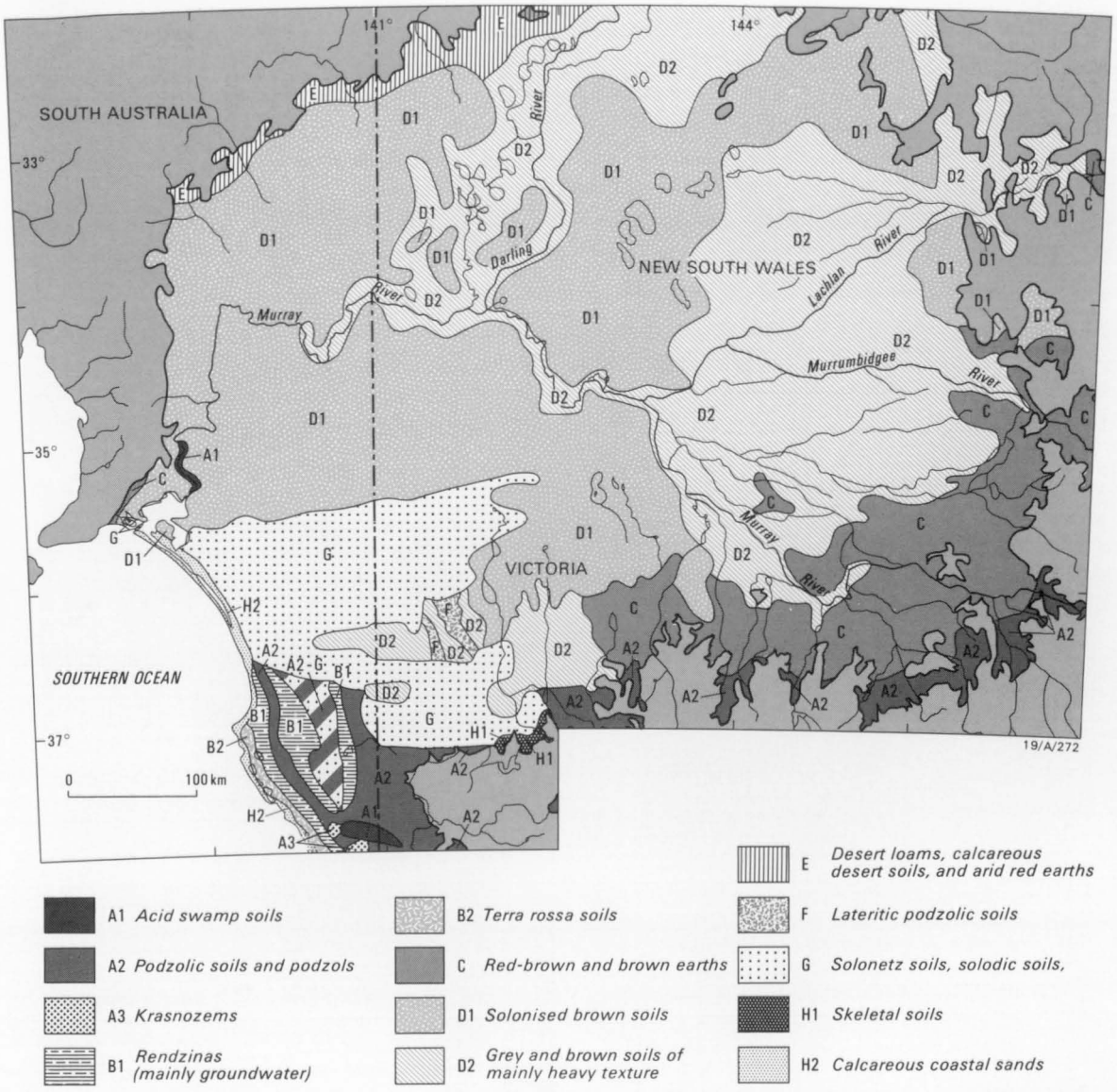

Fig. 13. Soil types of Murray Basin – after Stephens (1963), *Atlas of Australian Resources* (2nd Series), Department of National Development, Canberra.

tions, whereas the solonized brown soils overlie a variety of aeolian units including the Woorinen Formation, unnamed Qdp sand plain, and parts of the Molineaux–Lowan Sands. Solonetz soils, solodic soils, and solonchaks overlie the more mobile parts of the Molineaux–Lowan Sands (G). Podzolic soils and podzols (A2) cover the highland valleys of the southeast, and grade into red-brown and brown earths (C) on the flanking plains. Adjacent to the northwest margin of the basin, desert loams, calcareous desert soils, and arid red earths (E) flank the Flinders Ranges.

The coastal plain in the southwest of the Murray Basin has been uplifted during the last 700 000 years, and consists of stranded coastal beach ridges (Bridgewater Formation) and inter-ridge deposits (Padthaway Formation), on which several soil types have formed (Fig. 13). These include podzolic soils and podzols (A2), solonetz soils, solodic soils, and solonchaks (G), rendzinas (B1) in areas where the groundwater table reaches the surface, as well as acid swamp soils (A1), krasnozems (A3), and terra rossa soils (B2). Acid swamp soils (A1) are also found in the lower tract of the Murray River valley, which is of very low gradient and frequently waterlogged. Two minor soil types are found in western Victoria: skeletal soils (H1) near the Dundas Tableland in the south, and lateritic podzolic soils (F) associated with Pliocene stranded coastal ridges southwest of Lake Hindmarsh.

A fuller description of the various soil types in the Murray Basin can be found in G.C. Stephens'

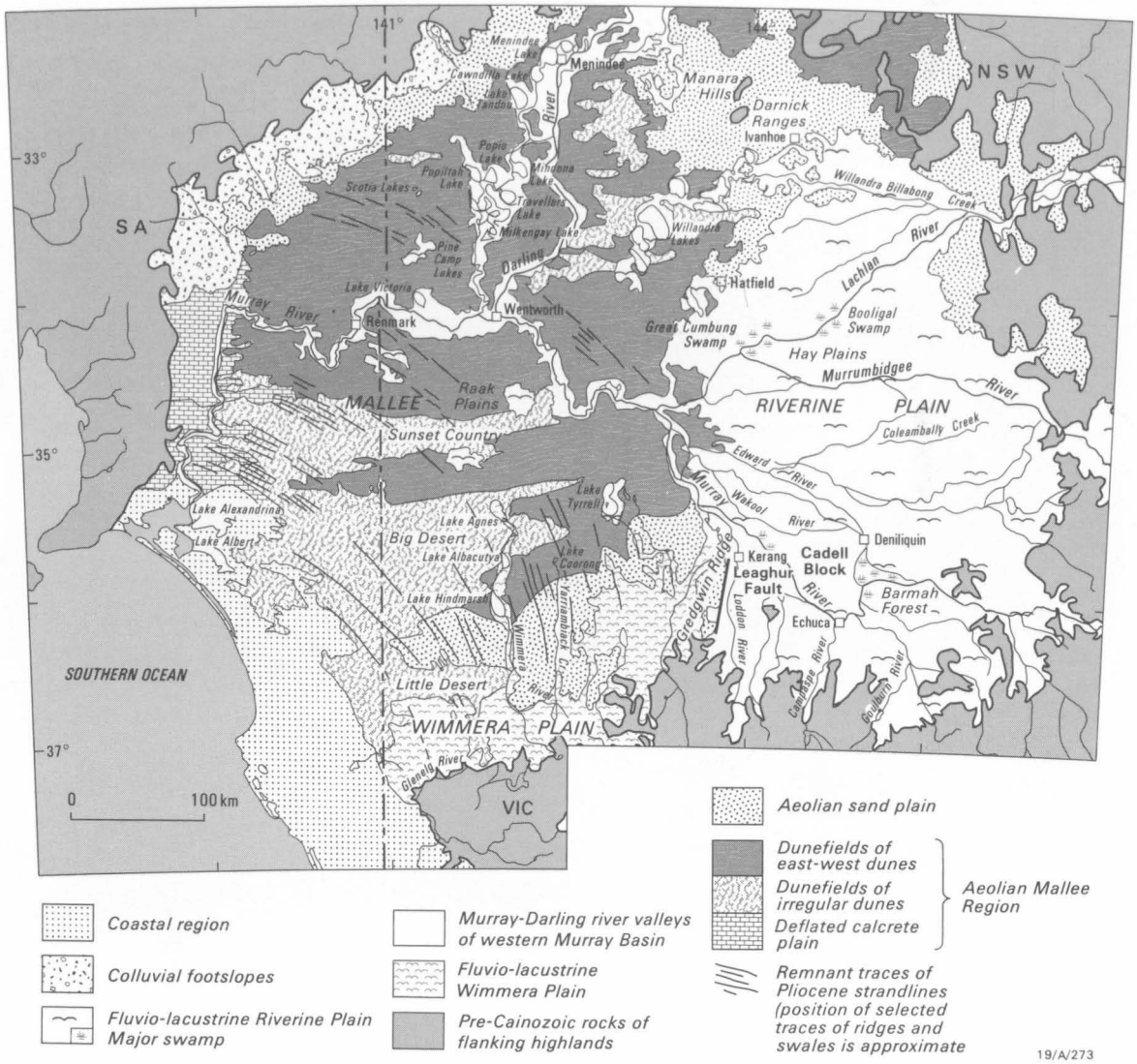

Fig. 14. Geomorphic regions of the Murray Basin.

(1963) *Atlas of Australian Resources* and in Butler & Hubble (1978) – from which the above outline has been much generalized.

Geomorphic subdivisions

The flat-lying surface of the Murray Basin can be subdivided into seven major geomorphically distinct regions (Fig. 14):

(1) Riverine Plain. In the east, the extensive Riverine Plain forms an almost flat surface of coalesced alluvial floodplains, dominated by fluvial processes and traversed by the westerly flowing Murray, Murrumbidgee, and Lachlan Rivers, their tributaries and anabranches. A distinctive tree-less region, extending over central, northern and western areas of the Riverine Plain, is known as the 'Hay Plains'.

(2) Wimmera plain. In the 'Wimmera', south of the basin, flanking the Victorian highlands, a narrow zone of northerly flowing streams, dominated by fluvio-lacustrine processes and locally blanketed by silty aeolian loess deposits, forms the Wimmera plain.

(3) Mallee region. The distinctive aeolian landforms and vegetation of the Mallee region underlie much of the flat to undulating western surface of the basin.

(4) Unnamed 'sand plains'. The Mallee dunefields are flanked to the north and southeast by unnamed geomorphic regions of 'sand plain'. These regions consist mainly of fluvio-lacustrine plains blanketed by thin veneers of aeolian sand and loess deposits.

(5) Murray–Darling River valleys of the western Murray Basin. In the west and northwest, the Mallee dunefields are traversed by the entrenched river valleys and associated floodplain and lake complexes of

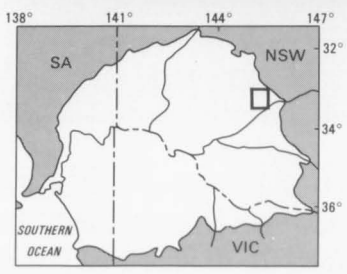

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Fig. 15. Photomosaic of Willandra 1:100 000 Sheet area showing fluvial distributaries of Lachlan River and Willandra Creek, in northern Riverine Plain.

the lower Murray River, the Darling River and the Darling Anabranch. These valleys form narrow but significant geomorphic zones, where fluvial processes predominate within an otherwise aeolian-dominated landscape. In South Australia, the Murray River flows within a narrow gorge ('Murray Gorge') entrenched within older up-faulted Cainozoic sedimentary rocks.

(6) Colluvial footslopes. In places, the basin margins and tributary highland valleys are blanketed by colluvial footslopes and debris aprons. These are particularly well developed over the up-faulted northwestern margin of the basin.

(7) Coastal region. To the southwest of the Mallee dunefields, a region of stranded beach ridges and narrow inter-ridge fluvial plains and swamps forms a recently emergent coastal plain in southeast South Australia.

Riverine Plain

The Riverine Plain of the eastern Murray Basin covers 77 000 km^2, extends 500 km north–south and up to 300 km east–west. It is underlain by Late Cainozoic fluvio-lacustrine sediments, and is traversed by an extensive network of major rivers draining into the basin from the northern and western flanks of the southeastern highlands (Fig. 14). The rivers include the northerly and northwesterly draining Murray River and its Victorian tributaries – the Loddon, Campaspe, Goulburn and Ovens Rivers – as well as the westerly flowing Murrumbidgee River and southwesterly flowing Lachlan River. To the east and south, sediments of the plain onlap the southeastern highlands, and to the west are partly blanketed by the encroaching dunefields of the Mallee region. To the northwest of the plain, concealed sediments of former distributaries of an ancestral Lachlan River are linked with those of the Darling River beneath an extensive aeolian sand plain. The surface of the plain is characterised by extremely low gradients and is virtually flat-lying with an average elevation of 120 m where it onlaps the highlands in the east, descending through a gradient of less than 20 cm/km to an elevation of 65 m at its western extremity.

The arcuate shape of the western margin of the Riverine Plain, as well as the direction of flow of many of the rivers, are primarily structurally controlled and reflect the arcuate configuration of underlying basement elements and the orientation of fracture sets. In New South Wales, for example, the westerly courses of the Lachlan River and its distributaries are thought to have been defeated by the concealed ridges of the Ivanhoe Block (Fig. 4) at the northwestern margin of the Plain. The block is only locally exposed at the surface in the form of outcrop of Devonian rock (Manara Hills, Manfred and Darnick Ranges), but the Iona ridge at the eastern margin of the block is marked by a southwesterly trending topographic ridge which rises some 50 m above the general level of the Riverine Plain (c.f. Odins & others, 1985). In the southwest, the Plain is separated from the Wimmera plain and adjacent Mallee landscape by the Gredgwin Ridge, a surface feature that overlies shallow basement (e.g. exposure of Lake Boga Granite) uplifted to the west of the Leaghur Fault (Fig. 14).

Where the Lachlan and Murrumbidgee Rivers emerge from the highlands onto the Riverine Plain, low-gradient, topographically subtle, alluvial fans extend a few tens of kilometres into the plains, but rapidly grade downstream into a distributary plain. The distributary rivers and streams traverse the Riverine Plain in an initial radiating pattern of interconnected channels (Fig. 15). The major trunk streams reconverge, however, towards the central-western apex of the Riverine Plain in BALRANALD, where the Lachlan River joins the Murrumbidgee River (via a small creek), which in turn flows into the Murray River to form a single large channel. The Murray River exits from the Riverine Plain and enters a narrow valley – the 'Murray Valley Trench' – entrenched within the aeolian landscapes of the Mallee region.

The present-day rivers of the flat-lying Riverine Plain form narrow meander belts within restricted floodplains, which are 1.5 to 5 km wide and entrenched some 1.5 to 5 m below the general level of the plain (Butler & others, 1973). Billabongs – oxbow lakes and other small perennial and ephemeral lake types – are common within the confined modern floodplains and within abandoned, but occasionally flooded former channels. The major trunk rivers are characterised by anastomosing channels (Mitchell, 1839) and effluent distributaries (Hills, 1940b, 1975; Bowler, 1978a), as well as an array of associated lacustrine features. The anabranches reconverge several tens of kilometres downstream, whereas other distributaries terminate in swamps and lakes or link up with entirely separate rivers. Some distributaries are dissipated within a network of channels locally forming 'playettes' (Macumber, 1968; Hills, 1975). Large swamps are particularly well developed along the course of the lower Lachlan River, which discharges into the

Booligal and Great Cumbung Swamps (BOOLIGAL).

The complex distributary patterns can partly be related to subtle structural control and partly to the low gradient of the plains. In the south of the Plain, the northwesterly flow of the Murray River has been impeded and disrupted by uplift of the Cadell Block (Fig. 16; Harris, 1939; Bowler & Harford, 1966a,b; Pels, 1964b; Bowler, 1967). At times in the past, the main channel was deflected to the north until it turned again to the northwest into the Edwards River and other distributaries at the northern margin of the Cadell Block, near the present site of Deniliquin. The most recent renewed uplift of the structural block has resulted in diversion of the main channel of the present-day Murray River to the south, where it resumes a northwesterly course at Echuca. The down-faulted area of ponded drainage to the east of the Cadell Fault is subject to seasonal flooding and is known as the Barmah Forest Swamp (Fig. 16). The entrenched river courses of the Riverine Plain are readily identified on aerial photographs and Landsat imagery by the presence of a seasonally inundated forest, and swamp vegetation. Flooding of the Murray, Murrumbidgee and Lachlan Rivers accompanies spring-time rain and meltwaters from the southeastern highlands. During summer droughts, flow rates are very much reduced in the trunk streams, and distributary channels dry up to form a series of billabongs.

A number of fossil fluvio-lacustrine features are readily apparent on aerial photographs of the Riverine Plain. The more recently active of these former channel courses, referred to as 'ancestral streams' by Pels (1964a,b), can be related to the modern river systems. The sediments in these channels are correlated with the Quaternary Coonambidgal Formation (Qa), whereas remnant traces of inactive meandering palaeochannels are referred to as 'prior streams', which form a surface component of the Upper Cainozoic Shepparton Formation (TQs). As described under the appropriate stratigraphic unit, some of the ancestral and prior stream channels, particularly those in the southeast of the Riverine Plain, display distinctive meander-wavelength and channel sediment-load characteristics, thought to reflect past fluctuations in climatic conditions. Sections of these inactive meander belts are defined by low forest vegetation and remnant strings of small lakes and billabongs. At present, most rivers carry a suspended sediment load, although as discussed later (see TQs, Qa) part of the sediment cover of the Riverine Plains was deposited under seasonally higher flow regimes than those which now prevail, and many of the older fluvial channels appear to have carried a heavy bed-load.

Numerous ephemeral lakes and swamps occur throughout the Riverine Plain in association with both active and inactive meander belts. In addition, extensive areas of former and recently re-activated groundwater discharge complexes are well developed adjacent to the western margins of the Riverine Plain. For example, an important zone of fossil discharge sites is located in the Hatfield region adjacent to the lower Lachlan River (see Figs 136, 150), and a complex of saline terminal and groundwater discharge lakes and playas is associated with the lower Loddon River, near Kerang (Mitchell, 1839; Macumber, 1968). Saline groundwater discharge, in association with aeolian transport of salts across the plains, has resulted in the removal of vegetation, leaving some areas susceptible to wind erosion, thus leading to development of irregular 'scalds' and clay pans which range from a few square metres to several square kilometres in area (Beadle, 1948; Pels, 1964a; Jones, 1969; Rowan & Downes, 1963; Butler & others, 1973).

Aeolian 'parna' dust and silt deposits are found over large areas of the surface of the Riverine Plain and are intercalated with the younger fluvial sediments (Butler, 1956; Butler & Hutton, 1956; Butler & others, 1973). Other aeolian features include lunettes (transverse crescentic dunes) adjacent to the eastern margins of lakes and fossil lakes, as well as source-bordering dunes. These latter dunes formed at sites where channel sands were reworked into small dunefields, which are now eroded to form low sand hills with an elevation of up to 20 m above the general level of the plain. A number of dunefields also flank the eastern and northern rim of the Riverine Plain, where sands have been dropped by winds rising over the highland areas to the east.

Wimmera plain

The 'Wimmera' is a district extending north of the Little Desert, but south of the 'Mallee', in western Victoria. The Wimmera plain is a relatively small (15 000 km^2) fluvio-lacustrine plain which fringes some 300 km of the northwest Victorian highlands (Fig. 14), and extends to the north where it is onlapped by aeolian 'sand plains' and landforms of the Mallee region. The plain forms a southwestern

Fig. 16. Southern Riverine Plain – LANDSAT scene showing Barmah Forest region, and disruption to flow of Murray River east of up-faulted Cadell Block. Main channel of Murray River currently flows around southern end of block, past Echuca, whereas a major distributary – the Edward River – flows around the north, past Deniliquin, along a former course of the Murray River.

extension of the Riverine Plain, but the rivers draining the Wimmera plain, with the exception of the Avoca River, neither cross the Mallee dunefields nor reach the Murray River to the north, and they end in terminal lakes such as Lake Agnes and Lake Tyrrell. Discharge from rivers, such as the Wimmera and its distributary Yarriambiack Creek, is dissipated partly by recharge into near-surface aquifers, and partly by evaporation in large lake complexes, such as Lake Hindmarsh and Lake Albacutya. The northerly to northwesterly trending drainage patterns of the Wimmera plain have been influenced both by underlying basement trends and by a series of northerly trending, topographically subdued, partly eroded and largely buried Pliocene strandline ridges. In the southwest, these strike ridges achieve an elevation approaching 200 m.a.s.l. – some 60 m above the general level of the fluvial plain. Drainage channels in the swales between these older sand ridges persist for up to 150 km to the north-northwest, and have deposited fluvio-lacustrine sediments. Rivers in the southwest of the Wimmera plain have been captured by the Glenelg River, which drains to the Otway Basin to the south.

Mallee region

The 'Mallee' is the name commonly given to that part of the western Murray Basin which is dominated by aeolian landforms and 'mallee' vegetation. The region is characterised by widespread dunefields (Fig. 14), with internal drainage patterns, and a semi-arid climate. 'Mallee' is an aboriginal term derived from "mali" – the water mallee whose roots were an important source of water (Tindale, 1974) – and is used collectively to describe numerous species of the genus *Eucalyptus* having the ability to develop a multi-stemmed habit. The Mallee region has a semi-arid climate, with predominantly internal drainage within widespread dunefields (Fig. 14).

There are several types of dunefields within the Mallee region (Fig. 14 and accompanying 1:1 000 000 scale geological map). These include:

(a) East–west longitudinal dunes (Woorinen Formation), which are the most common type. These dunes have subdued crests and flanks, and are separated by broad swales and sand plains (see Figs 131, 134). They are largely stabilised by vegetation.

(b) Remobilised Woorinen dunes form sub-parabolic to irregular locally mobile dunes, within elongate dunefields (Qdu) that are particularly well developed in the New South Wales portion of the Mallee (see Fig. 151).

(c) Extensive tongue-like dunefields, with irregular to sub-parabolic, locally linear, and sharp-crested dunes, form the Big Desert, Little Desert, and Sunset Desert in western Victoria and adjacent areas of South Australia (see Figs 131, 132). The sands (Qdm – Molineaux Sand in South Australia, and equivalent Lowan Sand in Victoria) are unconsolidated and locally mobile, and dunes are tightly packed, with narrow interdune corridors and local sand plains.

(d) Small, source-bordering dunefields occur adjacent to the Murray River in South Australia (Bunyip Sand). These are derived from sand blown out of the Murray valley by the prevailing westerly winds (see Figs 153, 154, 155), and are active today.

In addition to the dunefields, the Mallee region also contains dry, ephemeral and semi-permanent lakes, with flanking lunettes in many places. These are associated with major drainages (the Murray River, Darling River and its Anabranch), and ephemeral streams (e.g. Willandra Creek, Wimmera River), as well as groundwater discharge zones (e.g. Raak Plains and Lake Tyrrell). Aeolian processes are locally active within the Mallee region, and have in some areas been enhanced by land clearance since European settlement. Most of the Mallee, however, consists of fossil Late Pleistocene landforms.

'Sand plains'

The 'sand plain' regions of the Murray Basin lie between the aeolian dunefields of the Mallee region and the ranges and foothills of the basin margins, mainly in the north to northwest (Fig. 14). They consist of extensive areas of flat to gently undulating plains, that have many local fluvio-lacustrine depressions. In the north, the sediment of the sand plain forms a distinctive morphostratigraphic unit (see 'Qdp'). For convenience, the sediments of narrow aeolian-modified sand plains adjacent to the entrenched valleys of the Darling River and Anabranch are also included within the morphostratigraphic unit Qdp (see accompanying map), although these areas are smaller than those near the basin margins. They have a slightly different origin (see 'Qdp'), and consist of a veneer of aeolian sand, silt, and clay with a high salt content, derived largely from adjacent deflated lake floors and claypans. An additional region of aeolian 'sand plain' is located in the south (part of 'Wimmera'), where it forms a flat-lying transitional zone between the fluvio-lacustrine sediments of the Wimmera plain and the dunefields of the Mallee. The boundaries of the sand plain

regions are transitional and only approximately defined.

The sand plains were first recognized as a distinctive geomorphic zone on MANARA (Bryan, 1966), MENINDEE (Rose, 1967), and IVANHOE (Bryan, 1968). Additional areas were identified in New South Wales by Bowler & Magee (1978). Rogers (1978) regarded the sand plain on CHOWILLA as transitional between the Pooraka Formation (colluvial footslopes) and the Woorinen Formation (Mallee region), but distinctive enough to be mapped separately. Bowler & Magee (1978) recognized areas of "thin sand on plain with mallee vegetation", both between the Mallee dunefields and the ranges, and adjacent to some rivers and lakes.

The sand plains of the Murray Basin are typically flat to very gently undulating, with a sparse vegetation of Mallee-type shrubs, hardy grasses and a few clumps of spinifex in the northwest. The plains are in places interrupted by low sand dunes, which are normally orientated east–west (similar to those of the Woorinen Formation). Calcrete is commonly developed near the surface of these plains, and large horizontal sheets are locally exposed by erosion. In the north, drainage is largely internal, with numerous small claypans and depressions, and rainfall runoff tends to occur as sheetwash rather than form small intermittent streams. The few ephemeral streams which cross the northern sand plains region have headwaters in the adjacent ranges.

Murray–Darling River valleys of the western Murray Basin

The floodplains of the lower Murray, Darling and Darling Anabranch occur within entrenched valleys at a general level some 10–30 m below the adjacent aeolian landsurface. Near Menindee, the Darling River is just 50 m above sea-level and together with its anabranches, such as Talyawalka Creek, forms an extensive aeolian-modified floodplain with associated lake complexes, up to 100 km wide (see Fig. 156). In contrast, the lower Darling River floodplain is only some 2–3 km wide and at Wentworth is some 30 m above sea-level. The Darling Anabranch is also associated with extensive lake complexes (see Figs 140, 142), which are generally dry but flooded every few years following summer monsoonal rainstorms in the headwater catchments of the Darling River and its tributaries in southern Queensland. In places, the floodplains of the Darling River and Darling Anabranch have been strongly modified by aeolian processes, and fluviolacustrine sediments are frequently overlain by subdued elliptical dune forms. In addition, the many large lakes of the Darling and Darling Anabranch form major morphological features entrenched 20–30 m within the aeolian landscape. Large lake floors, such as Tandou and Travellers Lake (see Fig. 141), are elliptical to kidney-shaped with north–south dimensions up to 19 km and east–west dimensions up to 15 km. The eastern margins of the lake basins are flanked by curvilinear lunette ridges, locally in excess of 40 m above the adjacent lake floor.

The Murray River is subject to seasonal flooding, generally associated with spring meltwaters from the southeastern highlands. West of Boundary Bend (BALRANALD), the Murray River is confined to the relatively narrow 'Murray River Trench' up to 10 km wide. Near the tri-State border, the floodplain is confined within a zone 5 km wide, and farther west narrows to a width of only 1–2 km in the Murray River Gorge extending from near Renmark to Lake Alexandrina at the mouth of the river (Twidale & others, 1978). The 'trench' and upper tracts of the gorge are cut into progressively older Quaternary clays and Pliocene sands (Fig. 8), while farther downstream the river valley is confined within cliffs of Miocene limestone (see Fig. 165).

Within the aeolian landscapes, the Murray River essentially acts as an effluent drain, and the quality of the river water greatly deteriorates downstream. This is mainly because the river is entrenched within a system of near-surface aquifers with highly saline groundwaters which locally discharge into the river, but is also partly due to evaporation and a lack of dilution from tributary streams. Recharge of shallow aquifers from the Murray, Darling and Darling Anabranch is partly prevented by the presence of a clay seal forming the river beds.

Colluvial footslopes

The colluvial footslopes of the Murray Basin mainly comprise a narrow band of talus and outwash deposits, located within highland valleys and adjacent to most of the basin margins (see accompanying geological map). The piedmont deposits of highland valleys in the Southeast Australian Highlands, Mt Lofty Ranges, and Flinders Ranges grade into colluvial fans at the edge of the Murray Basin proper (Fig. 14). The valley deposits may be very coarse grained, and in many places are iron-cemented, with calcretes, or less commonly silcretes, developed within them. On the other hand, the colluvial outwash fans are normally at low to very low angles,

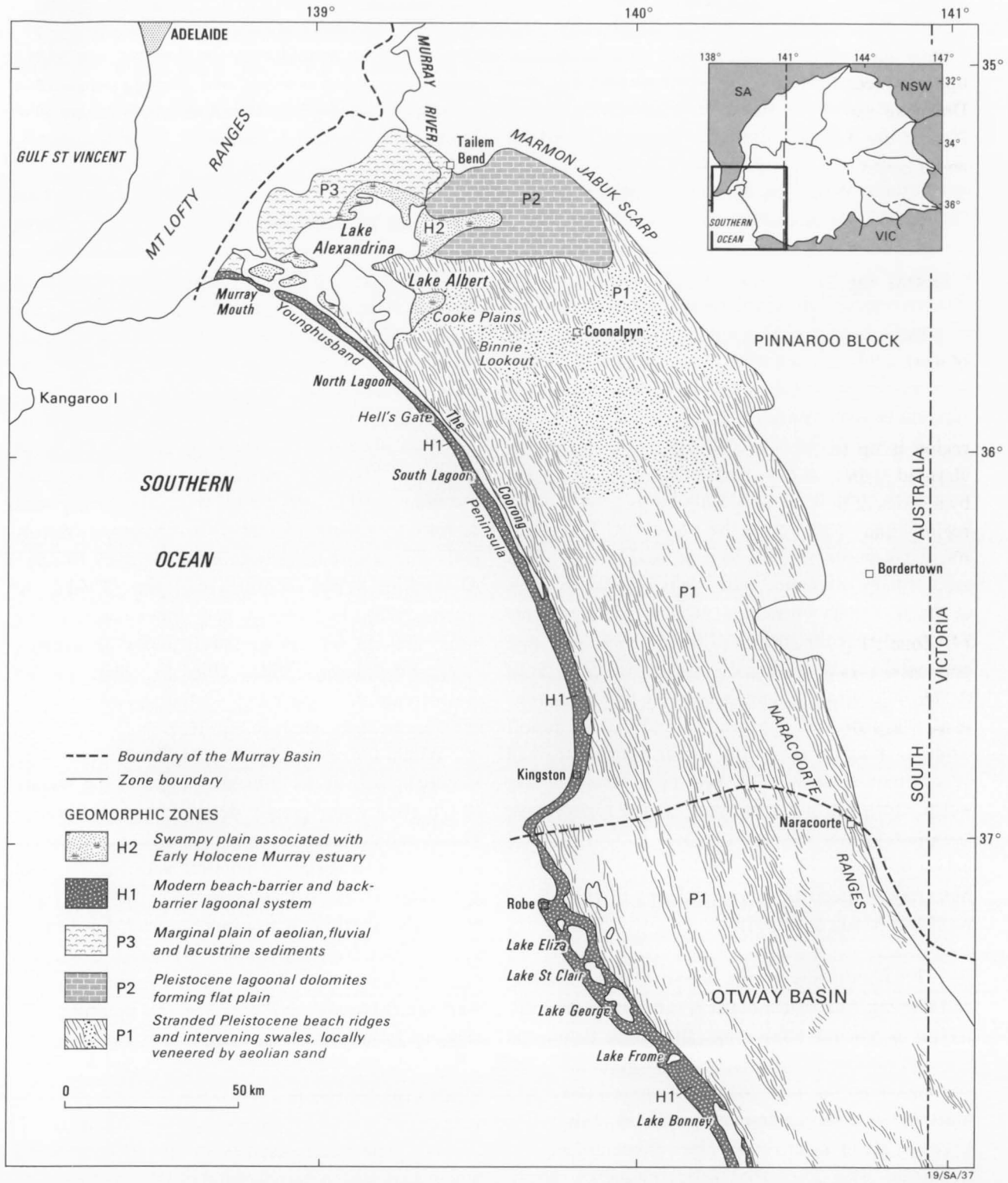


Fig. 17. Geomorphic zones of the coastal region.

with finer-grained sediments, and grade almost imperceptibly into the sediments of the Murray Basin proper.

There is a marked contrast between the highland valleys of the southern and eastern margins of the Murray Basin, and those of the northern and western flanks. In Victoria, the fluvial Shepparton and Coonambidgal Formations extend into the highland valleys (Lawrence, 1975), whereas in South Australia the highland valleys are infilled by the colluvial Pooraka Formation, which spills out onto the edges of the Murray Basin. This contrast is caused partly by climatic variations and partly by the differing tectonic histories of the Southeast Australian Highlands and the Mt Lofty and Flinders Ranges. The former have been topographically high since at least the Per-

mian (C.D. Ollier, BMR, personal communication, 1984), whereas the latter ranges were undergoing uplift as recently as the Pleistocene. Within the basin, Devonian sandstones of the Darnick and Manfred Ranges are flanked by high-angle aprons of talus; and a series of low-angle alluvial fans are associated with the Marmon Jabuk Scarp, an erosional feature of Pleistocene age in southeastern South Australia.

Coastal region

The coastal region of the Murray Basin consists of a recently emergent (younger than 0.7 Ma) zone in southeast South Australia between the Pinnaroo Block and the Southern Ocean (Fig. 14). The coastal region is up to 100 km wide, and is essentially an elevated plain standing at 10–30 m.a.s.l., interrupted by a series of large stranded coastal dune ridges. The region can be subdivided into five unnamed physiographic areas (Fig. 17), three of Pleistocene age (P1, P2 and P3), and two of Holocene age (H1 and H2):

(1) Zone P1 (Fig. 17) covers by far the largest area, and incorporates a series of stranded Pleistocene beach ridges (the Bridgewater Formation) and inter-ridge deposits (the Padthaway Formation). The highest of these ridges are the East Naracoorte Range in the south (up to 130 m.a.s.l.), abutting the southern Pinnaroo Block, and an unnamed range at Binnie Lookout in the north (up to 170 m.a.s.l.), where the sedimentary rocks are underlain by a basement high (the Padthaway Ridge). Cook & others (1977) recognized at least twenty strandline ranges (see 'Bridgewater Formation'). The inter-ridge corridors are very flat and low-lying, with numerous swamps and small lakes. In the north, these ridge and inter-ridge deposits are overlain by a veneer of younger aeolian sand.

(2) To the north of the beach-ridge sequence, a flat plain (P2) occurs between Lake Alexandrina and the Marmon Jabuk Range. This was formed by a marine incursion during the Early Pleistocene, and is bounded by an erosional escarpment in the east. An unnamed lagoonal dolomite unit was deposited during this Early Pleistocene marine transgression (see 'Qpu').

(3) The third Pleistocene coastal zone (P3) is a narrow plain between Lake Alexandrina and the Mt. Lofty Ranges. This is composed of fluvial, lacustrine, and aeolian sediments, and is peripheral to the Murray Basin proper.

(4) The same processes which formed area P1 are active today. The modern beach and coastal-dune barrier is the Younghusband Peninsula (see 'Semaphore Sand'), with a restricted back-ridge lagoon known as the Coorong (see 'Qhl'). These features, together with beaches and coastal lakes south of Kingston, make up zone H1 (Fig. 17). The Coorong is being slowly infilled with chemical and clastic dolomitic sediment, with the Holocene lagoon retreating towards the northwest (Von der Borch, 1976).

(5) The fifth zone within the coastal region is the modern estuary of the Murray River (H2). This includes Lakes Alexandrina and Albert, associated waterways, and areas of relict lacustrine sediments deposited during times of higher lake levels. The latter include the St Kilda Formation, and the gypsiferous sediments of the Cooke Plains Embayment.

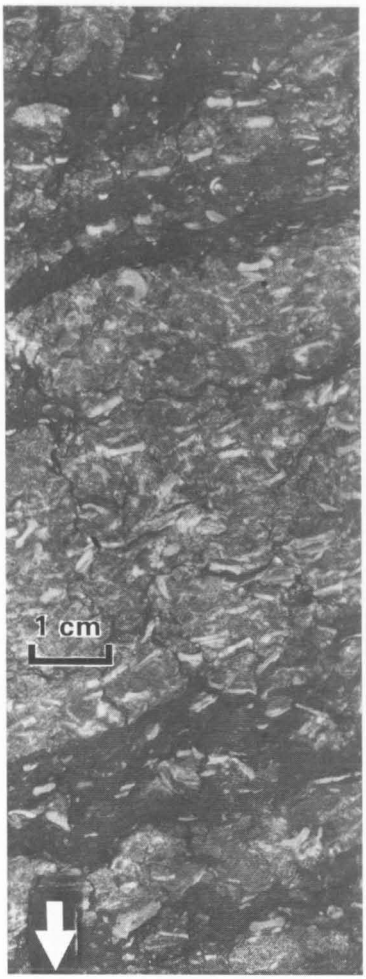
The entire stranded beachridge sequence has been uplifted since about 0.7 Ma ago (Cook & others, 1977). The unnamed lagoonal dolomites (Qpu) in area P2 may be slightly older (about 0.9 to 0.8 Ma). In places, the Pleistocene sediments are covered by a veneer of younger aeolian material (usually Molineaux Sand). The coastal geomorphic zone extends south into the northern Otway Basin (Fig. 17). The coastline is prograding today, although glacio-eustatic fluctuations in sealevel during the Pleistocene caused temporary transgressions within the general tectonically related regression. Some of the Bridgewater Formation dunes represent multiple depositional events, and the modern Semaphore Sand overlies the remnants of an older, Pleistocene, beach ridge (Firman, 1973).

Geomorphology and palaeohydrology

Many of the present-day fluvio-lacustrine and aeolian geomorphic features of the Murray Basin are fossil landforms, formed during periods over the past 0.5 Ma, when groundwater levels were higher, but climates more arid. Many currently active salinas and ephemeral playas are entrenched 1–2 m within extensive areas of stranded lake floor and lunette sediments, which are now recognised as fossil groundwater discharge lake complexes. These occur both within the aeolian landscapes and at the western margin of the Riverine Plain (e.g. Raak Plains, Scotia Lakes, Hatfield complex; see Fig. 143). Many of these complexes (e.g. Willandra Lakes) are thought to have been last active when groundwater levels were significantly higher than at present. As discussed later (see 'Qdl' and 'Qly'), variations in the sedimentological character of the lunettes adjacent to

the lakes largely reflect past climatic and hydrologic conditions prevailing at the time of deposition, and record past salinisation events. The fossil deposits are much more extensive than their modern equivalents, indicating that salinisation of the landscapes was more widespread in the recent geologic past. Current land-use practices are causing groundwater levels to rise, thereby reactivating the natural processes responsible for salinisation events in the recent geologic past. Macumber (1968, 1978b, 1978c, 1983), for example, has related the reactivation of many surface geomorphic features, such as discharge springs and playettes in the lower Loddon valley, to rising groundwater tables. The Quaternary sediments mantling the Murray Basin record past fluctuations in groundwater tables and reflect the sensitivity of landform development in the basin to climatic variation between arid and semi-arid conditions.

4



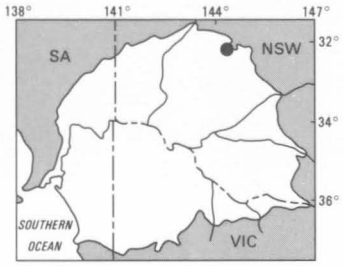


Fig. 18. Fossiliferous core sample of marine Lower Devonian sediments of the Amphitheatre Group of the Darling Basin – encountered in BMR Ivanhoe No. 1 bore (Passmore, 1981), beneath the northern margins of the Murray Basin.

STRATOTECTONIC FRAMEWORK OF THE MURRAY BASIN

Regional tectonic framework

The Murray Basin is almost entirely flanked by basement elements which form low mountain ranges or basement rises, and as a consequence forms an almost entirely closed basin of internal surface and groundwater drainage. The Cainozoic sediments of the basin form an extensive, but thin, platform-cover succession within which the thickest Cainozoic sediments (up to 600 m) occur in the main depocentre in central-western areas, with up to 400 m in a subsidiary depocentre beneath the western Riverine Plain. Elsewhere, the sediments are generally less than 200 m thick. As a result, Cainozoic sedimentation patterns, as well as present-day groundwater flow and surface discharge patterns, are strongly influenced by the shape of the basement elements underlying and flanking the basin.

To the west, the Murray Basin is flanked by Proterozoic and Lower Palaeozoic tectonic elements forming the Mount Lofty, South Flinders and Barrier Ranges (Fig. 2). In the northwest, these include the high-grade metamorphic basement complexes of the Proterozoic Willyama Block (South Australia) and Broken Hill Block (New South Wales; Figs 4, 19). In the west, the Cainozoic succession unconformably onlaps folded Upper Proterozoic and Lower Palaeozoic sedimentary rocks and metasediments of the Adelaide and Kanmantoo Fold Belts. In the southwest, the Murray Basin succession is connected to the Cainozoic sediments of the Southern Ocean and Otway Basin, but thins over the Padthaway Ridge. This basement feature is largely concealed and consists of northwesterly trending metasediments and Early Palaeozoic granitoids, which now form a

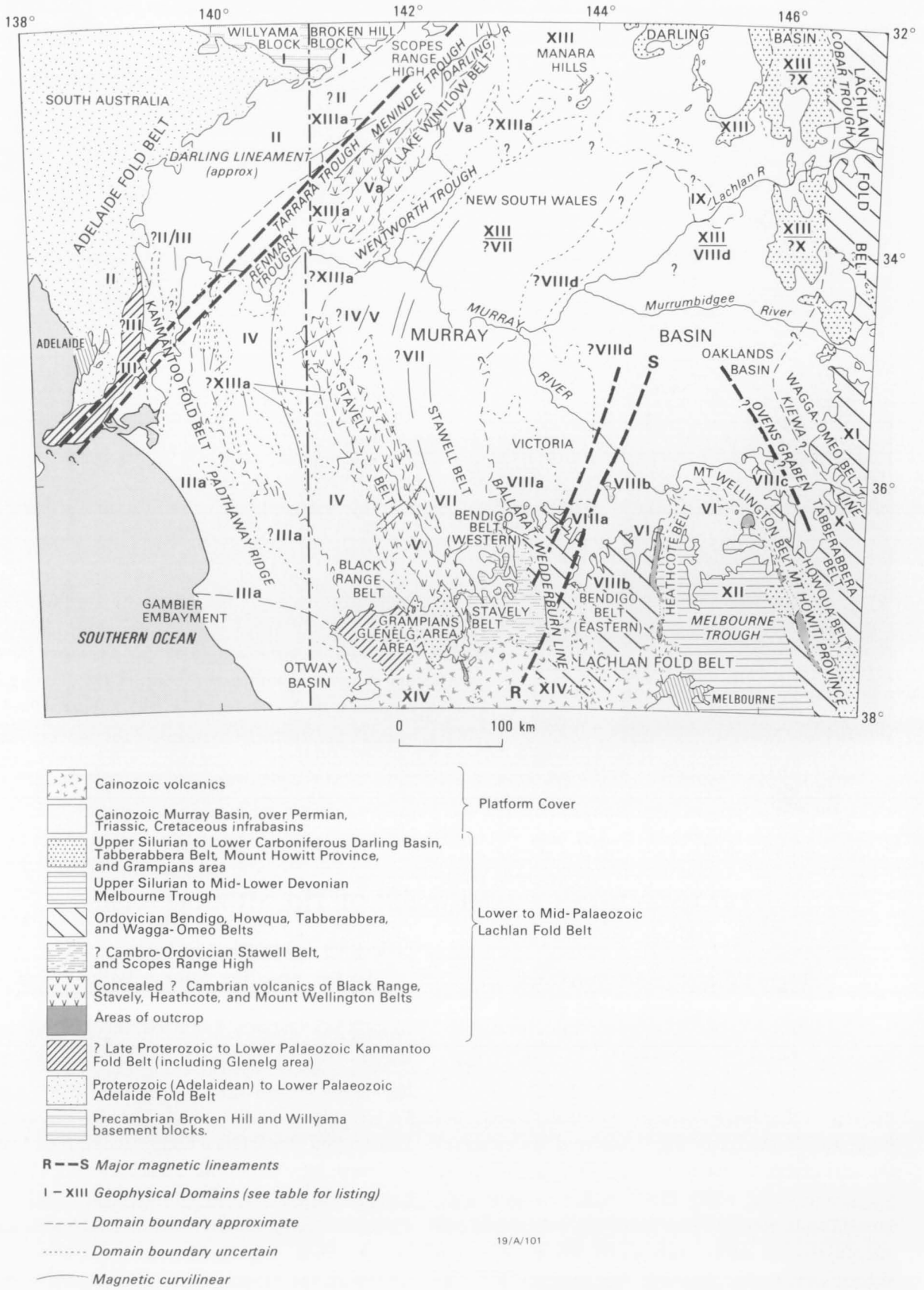


Fig. 19. Interpreted tectonostratigraphic belts and regional geophysical domains flanking and underlying the Murray Basin – based partly on interpretation of aeromagnetic data (see accompanying Table 2 and Fig. 162 for explanation of geophysical domains.

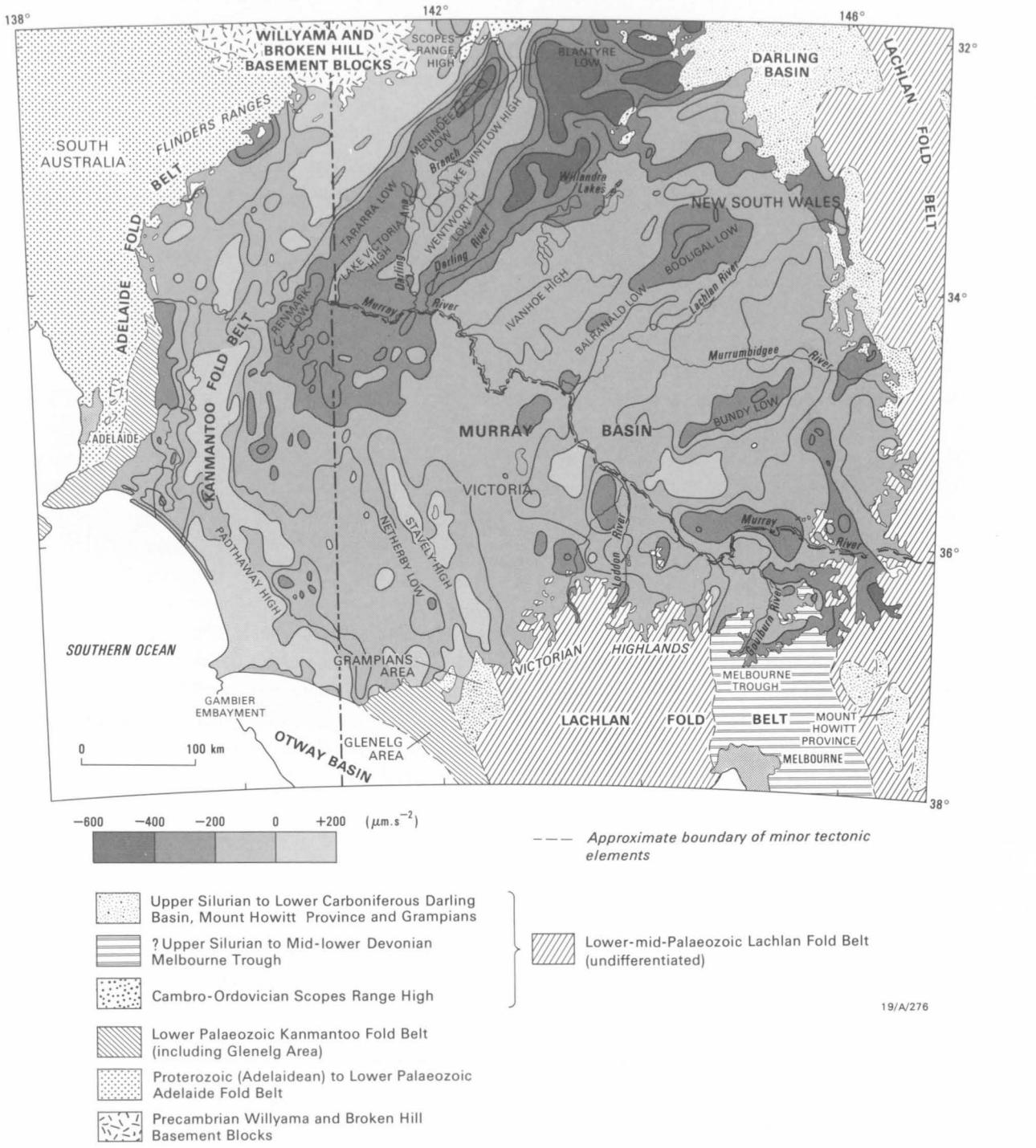


Fig. 20. Simplified regional Bouguer gravity anomaly map of the Murray Basin, and gravity-defined features.

southwestern rim to the Murray groundwater basin.

To the south, east, and north, the basin is flanked by deformed Palaeozoic rocks of the Lachlan Fold Belt, forming the ranges of the Eastern Highlands (Figs 4, 19). The Lachlan Fold Belt is itself a composite tectonic feature consisting of a collage of northerly trending belts of Cambrian to Lower Carboniferous sedimentary rocks, metasediments, and minor Palaeozoic basic and acid volcanics, intruded by extensive Siluro-Devonian granitoids. In the Victorian Highlands to the south of the Murray Basin, the Palaeozoic fold belt is locally overlain by Cainozoic basaltic lavas and pyroclastics. Rocks older than Cambrian have not been positively identified within the Lachlan Fold Belt, but many reconstructions have inferred the presence of underlying Precambrian crust (Rutland, 1973a,b, 1976, 1982; Scheibner, 1976, 1985). Structural belts of

deformed sedimentary and metasedimentary rocks flanking the Murray Basin to the south and east include the Stawell, Bendigo, Howqua, Tabberabbera, and Wagga-Omeo Belts, and the Melbourne Trough (Fig. 19). These structural subdivisions are in places separated by narrow, linear, greenstone belts (Black Range, Stavely, Heathcote, and Mount Wellington Belts). Northeasterly trending folded Upper Silurian to Lower Carboniferous sedimentary rocks of the Darling Basin (a late-stage component of the Lachlan Fold Belt) underlie parts of the northern Murray and are exposed in low hills to the north of basin. Deformation in the Lachlan Fold Belt ranges from intensely folded and metamorphosed to moderately folded and strongly indurated.

The folded and faulted tectonic elements flanking the Murray Basin extend beneath the thin Cainozoic succession, where they form shallow basement features. Borehole evidence (Brown & Stephenson, 1986) indicates that the Cainozoic basin is also locally underlain by poorly defined infrabasins, preserved in graben-like troughs and depressions within the faulted basement (e.g. Ovens Graben, Menindee, Tararra and Renmark Troughs; Figs 4, 19, 23). Beneath western areas these contain thick sequences of Devonian to Lower Carboniferous sedimentary rocks (equivalents of the Darling Basin to the north and the Grampians region to the south), and locally they also have discontinuous, erosional remnants of Upper Carboniferous–Lower Permian, Upper Permian, Triassic and Cretaceous post-orogenic, platform-cover sediments (see Chapter 5).

Interpreted tectonostratigraphic belts concealed beneath the Murray Basin

Few high-resolution seismic surveys and limited petroleum exploration drilling have thus far been undertaken in the Murray Basin. Consequently, little direct evidence regarding the true nature of underlying basement elements is available. The location and extent of concealed basement features have been identified mainly on the basis of regional geophysical patterns and trends. Many of the structural features shown on Fig. 19 (see also Fig. 162) were first identified on Bouguer gravity anomaly maps (Fig. 20; Plate 15). In general, Bouguer gravity lows were interpreted as indicating the presence of structural depressions with sediments, whereas zones of positive gravity anomalies were interpreted as basement highs (Fig. 20). In places, the basement is intruded by low-density granitoids which have complicated the interpretation of some gravity-defined depressions, and as a result the boundaries of many concealed structural features are poorly defined. The extent and configuration of the Wentworth Trough within the Wentworth 'Gravity Low' (Fig. 20), for example, have been disputed by Dampney (1977) and Vozoff & Cull (1981).

General structural trends within the basement beneath the Murray Basin can be seen on total magnetic intensity imagery (see 'Aeromagnetics' and Plates 16, 17; Tucker & others, 1985a,b; Brown & others, 1988). A number of 'domains' (shown on Fig. 19) have been defined mainly on the basis of magnetic character, refering to areas with magnetic patterns and trends distinctive from those in adjacent areas. The source of many of the magnetic anomalies beneath the Murray Basin is not yet known, and consequently, identifications of domains are preliminary and subject to revision. Despite this caution, the structural trends seen within the basement display a strong correlation with Cainozoic sedimentation patterns and surface geomorphic patterns. The likely age and tectonostratigraphic character of each concealed domain has partly been determined from the limited borehole data and partly by extrapolation of the geology of contiguous structural belts exposed in the flanking highlands. Brief synoptic summaries of the likely geological character of the domains flanking and underlying the Murray Basin are given in Table 2 (locations shown on Figs 19, 162). Various names have been applied to these basement features, but where possible the most commonly accepted nomenclature has been retained. An interpretation of the tectonostratigraphic framework of the Murray Basin region, based on an examination of the magnetic patterns is given in Brown & others (1988). M.G. Farrand (S.A.D.M.E., pers. comm., 1989) has subsequently identified substantial spilitic basalt, boninite, trachyandesite and metadolerite dykes between the Mount Lofty Ranges and the Glenelg area, and has suggested that the Padthaway Ridge area should be a separate domain.

Data sources. A review of the Proterozoic and Palaeozoic basement geology flanking and underlying the Cainozoic Murray Basin is beyond the scope of this Bulletin. Major descriptions of the basement geology, as well as interpretations of the evolution of the regional tectonic framweork, are given in the following: Glaessner & Parkin (1958), Parkin (1969), Thomson (1969b), Oversby (1971), Daily & Milnes (1972, 1973), Scheibner (1972, 1973, 1974, 1976, 1978, 1985), Webby (1972, 1976, 1978), Harrington & others (1973, 1974), Packham (1973), Harrington (1974), Morris & Nicol (1974), Crook & Felton

TABLE 2. GEOPHYSICAL DOMAINS FLANKING AND UNDERLYING MURRAY BASIN

Domain	*Interpreted structural belt*	*Age*	*Dominant rock types*
Domain I	Broken Hill Block (including Willyama Block)	Mainly Proterozoic	Basement migmatite, quartzofeldspathic metasedimentary & basic gneisses, Precambrian granitoids, basic & ultrabasic intrusives
Domain II	Adelaide Fold Belt	Late Proterozoic to Cambrian (mainly Late Proterozoic)	Weakly metamorphosed fluvio-deltaic, shallow-marine clastics, carbonates, evaporites & tillites, Ordovician granitoids
Domain III	Kanmantoo Fold Belt	?Late Proterozoic to Cambrian (mainly Cambrian)	Metagreywacke, phyllitic schist & gneiss of Kanmantoo, over ?Adelaidean rocks; Ordovician granitoids & rhyolite
Domain IIIa	Padthaway Ridge/?Kanmantoo Fold Belt	?Late Proterozoic to Cambrian (mainly Cambrian)	Metagreywacke, phyllitic schist & gneiss, Ordovician granitoids & rhyolite, mafic volcanics, basalt & dolerite, & gabbro-norite intrusives; ?Proterozoic basement beneath Padthaway Ridge
Domain IV	?Kanmantoo Fold Belt, partly under Domain XIIIa	?Late Proterozoic to Cambrian, beneath younger sediments	Metasediments, schist & gneiss of Kanmantoo, structurally intercalated with ?Adelaidean rocks; locally under (?Siluro)-Devonian sediments, Ordovician granitoids & ?volcanics
Domain V	Stavely Belt (including Black Range Greenstone Belt)	?Cambrian or older in age	Basic & andesitic volcanics, serpentinite, chert, volcaniclastic sediments, partly under ?Siluro-Devonian sediments, Siluro-Devonian granitoids & ?volcanics
Domain Va	Lake Wintlow Belt	?Cambrian (but possibly as young as Devonian)	Interpreted volcanics
Domain VI	Heathcote & Mount Wellington Greenstone Belts (Lachlan Fold Belt)	Mainly Cambrian	Volcanics, dolerite, gabbro, serpentinite, chert, shale
Domain VII	Stawell Belt (Lachlan Fold Belt)	Uncertain, probably Cambrian or older to Early Ordovician	Metamorphosed slate, greywacke, Devonian granitoids
Domain VIIIa	Western Bendigo Belt (Lachlan Fold Belt)	Mainly Ordovician	Turbiditic metasediment, magnetic & non-magnetic Devonian granitoids
Domain VIIIb	Eastern Bendigo Belt (Lachlan Fold Belt)	Mainly Ordovician	Turbiditic quartzose metasediments, non-magnetic Devonian granitoids
Domain VIIIc	Howqua/Tabberabbera Belt (Lachlan Fold Belt)	Ordovician under Devonian to Lower Carboniferous	Ordovician, turbiditic metasediments, under Devonian - Early Carboniferous non-marine sediments & volcanics, Devonian granitoids
Domain VIIId	Unnamed domain beneath Riverine Plain (Lachlan Fold Belt)	Mainly ?Ordovician	?Ordovician metasediments, ?Siluro-Devonian sediments, Devonian granitoids
Domain IX	Unnamed domain beneath northeast Riverine Plain (Lachlan Fold Belt)	Uncertain	?Igneous rocks
Domain X	Tabberabbera Belt (Lachlan Fold Belt)	Ordovician under Siluro-Devonian	Ordovician slate & quartzite, under Siluro-Devonian clastics, Siluro-Devonian granitoids
Domain XI	Wagga-Omeo Metamorphic Belt (Lachlan Fold Belt)	Mainly Ordovician	Quartzite, slate, schist & gneiss, Ordovician, Silurian & Devonian granitoids
Domain XII	Melbourne Trough (Lachlan Fold Belt)	Mainly Siluro-Devonian over Ordovician	Marine clastics, non-magnetic Devonian granitoids
Domain XIII	Darling Basin (Lachlan Fold Belt)	Silurian to Early Carboniferous (mainly Devonian)	Marine clastics beneath continental sandstone, conglomerate
Domain XIIIa	?Upper Silurian-Lower Carboniferous Infrabasins (Lachlan Fold Belt)	Silurian to Early Carboniferous (mainly Devonian)	Marine shale under thick non-marine sands (Devonian); locally under Permian & Cretaceous platform cover remnants
Domain XIV	Cainozoic volcanics of Victorian Highlands (Lachlan Fold Belt)	Cainozoic	Basaltic flows, plugs & dykes, lava fields of western Victoria

(1975), Beavis (1976), Daily & others (1976, 1979), Douglas & Ferguson (1976, 1988), Thomas & others (1976), VandenBerg & others (1976, 1982), Veevers & McElhinny (1976), Glen & others (1977), Milnes & others (1977), Crawford & Keays (1978), Doutch & Nicholas (1978), Gilligan & Scheibner (1978), VandenBerg (1978, 1986, 1988), Preiss (1979, 1987), Cas & others (1980, 1983), Crook (1980a,b), McWilliams & McElhinny (1980), Von der Borch (1980), Preiss & others (1981), Richards & Singleton (1981), Rutland & others (1981), Brown & others (1982), Brown & Cooper & others (1982), Buckland & Ramsay (1982), Jago & Daily (1982), Cas (1983), Cox & others (1983), Willis & others (1983), Crawford & others (1984), Wellman (1987), Buckland (1986), Cas & VandenBerg (1988), Crawford (1988), Wellman & Greenhalgh (1988), and Farrand (in press).

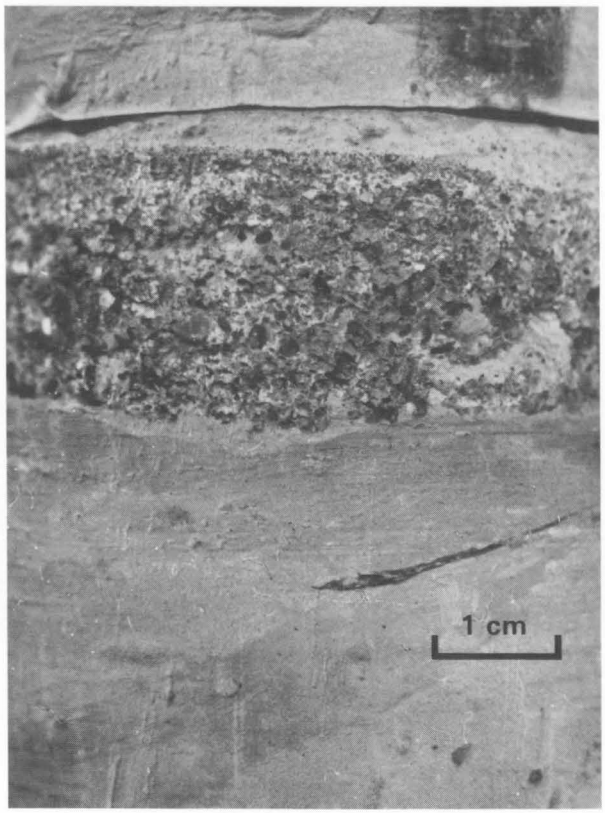
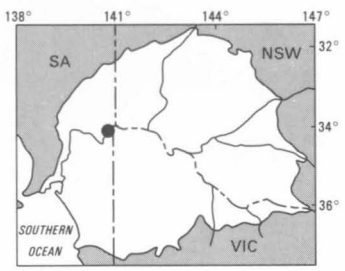


Fig. 21. Lower Permian Urana Formation equivalents from core 14 at 1097 m in Australian Oil Corporation North Renmark No.1 – a normally graded bed of Facies S1, interbedded with Facies M1 (see 'Lower Permian' for explanation).



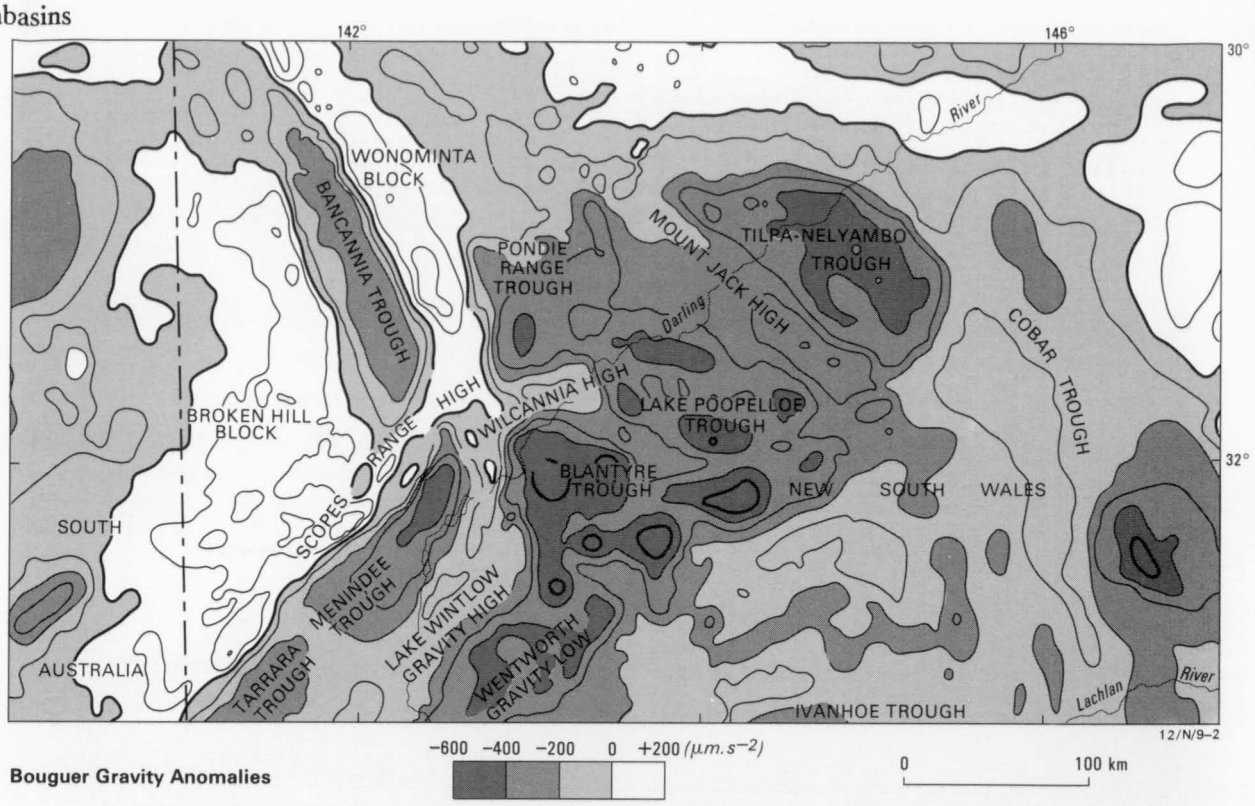
5

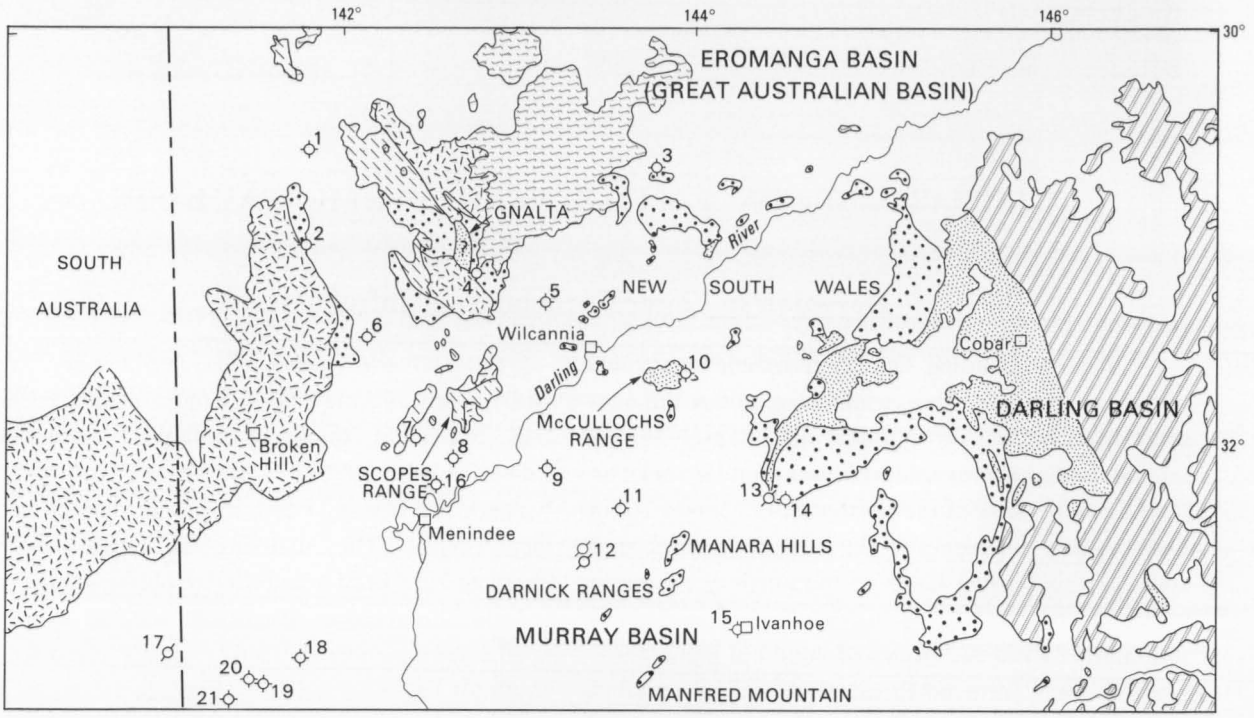
INFRABASINS CONCEALED BENEATH THE MURRAY BASIN

Devonian to Lower Carboniferous infrabasins

Northerly trending Devonian sedimentary rocks of the Lachlan Fold Belt, which crop out at the eastern margin of the Murray Basin, are intensely folded, faulted, and partly metamorphosed. Similar rocks extend beneath parts of the northeastern Murray Basin. Deformation diminishes to the west in the equivalent rocks of the Darling Basin to the north of the basin, where Devonian to Lower Carboniferous marine and non-marine rocks are broadly folded but unmetamorphosed. They form northeasterly trending anticlines and synclines, which in places extend beneath northern parts of the Murray Basin where they are locally exposed in the low hills of the Darnick and Manfred Ranges, and Manara Hills (Fig. 22). South of the Murray Basin, folded marine to non-marine successions of the Melbourne Trough and mainly non-marine Devonian rocks of the Grampians area – correlatives of the Darling Basin – are exposed in the flanking Victorian Highlands (Figs 19, 23). Deformed metasedimentary rocks of the Melbourne Trough have also been encountered in water bores beneath the Riverine Plain in northern Victoria (Tickell & Humphrys, 1979).

Bouguer gravity anomalies, aeromagnetic trends, and limited seismic and borehole evidence suggest that equivalent thick block-faulted Devonian to Lower Carboniferous infrabasins are preserved beneath the Murray Basin in poorly defined graben-like troughs. The structure of these troughs is characterised predominantly by northeasterly trends beneath the northern Murray Basin (Figs 20, 22) and northerly to northwesterly trends beneath the southern half of the basin (Figs 19, 20). Interpretations of seismic data suggest that the troughs beneath the western Murray Basin may contain a thickness of several kilometres of block-faulted, but relatively undeformed Devonian sedimentary rocks (Planet Oil, 1966, 1968; Beaver, 1973; Evans, 1977; Bauer & others, 1979; Brown & others, 1982). In the north, Evans (1977) interpreted up to 7 km of sediment, although the age of the basal part of the seismically defined sedimentary sequence has not been confirmed by drilling and it seems likely that part of the succession includes older Cambro-Ordovician and/or Silurian rocks. Farther south in the Tararra Trough, a thickness of approximately 2 km of Devonian





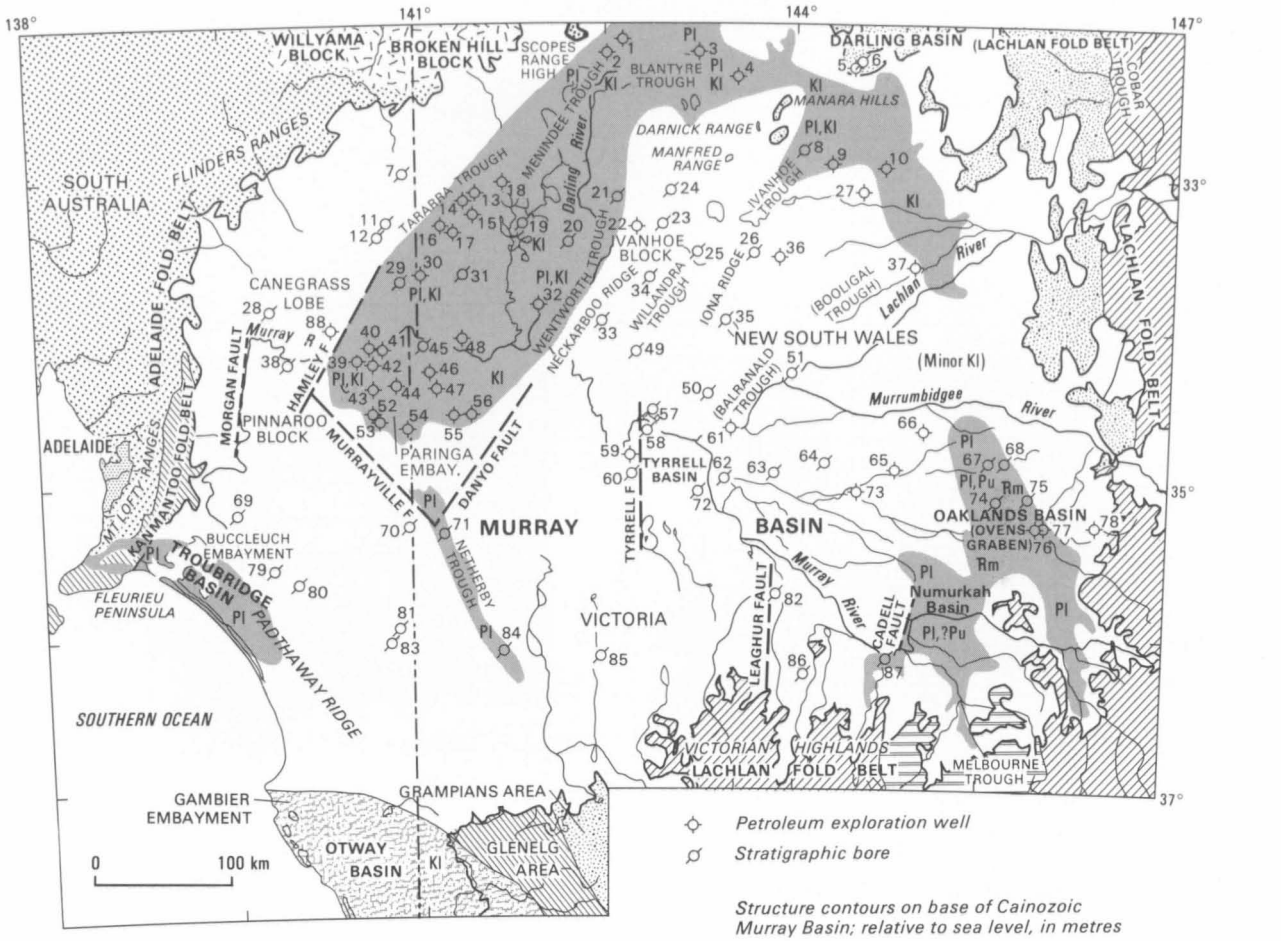
Generalised geology modified after 1:1 000 000 Geological Map of New South Wales (Pogson, 1972)

Petroleum exploration wells and stratigraphic bores

1 Bancannia North 1
2 Bancannia South 1
3 Mount Jack 1
4 Gnalta 1
5 Pondie Range 1
6 Jupiter 1
7 Byrndale 1
8 Blackgate 1
9 Blantyre 1
10 Poopelloe Lake 1
11 Mount Emu 1
12 BMR Manara 1, 2
13 BMR Ivanhoe 1
14 Berangabah 1
15 Ivanhoe 1
16 Pamamaroo 1
17 SADME Oakvale 1
18 Popiltah 1
19 Avery 1
20 Ironstone Tank 1
21 Kopi Plain 1

12/N/8-1

Fig. 22. Generalised geology, Bouguer gravity anomalies and concealed structural features of northern Murray Basin.



Petroleum exploration wells and major stratigraphic bores

1 Blackgate 1
2 Pamamaroo 1
3 Blantyre 1
4 Mount Emu 1
5 Berangabah 1
6 BMR Ivanhoe 1
7 Oakvale 1
8 D.M. Umalee 1
9 Ivanhoe 1
10 Conoble 1
11 Canopus 2
12 Canopus 1
13 Avery 1
14 Ironstone Tank 1
15 Kopi Plain 1
16 Ennisvale 1
17 Tararra 1
18 Popiltah 1
19 BMR Woodlands 1
20 BMR Manilla 1
21 BMR Mitfords Corner
22 Nambuccura 1
23 BMR Nambuccura 1
24 BMR Coronation 1
25 Lake Garnpung 1
26 BMR Arlington 1
27 Holey Box 1
28 Bungunnia Bore
29 Canegrass Bore
30 Nulla Nulla 1
31 BMR Warwick 1
32 Wentwoth 1
33 BMR Neckarboo 1
34 BMR Top Hut 1
35 BMR Iona 1
36 Dolmoreve 1
37 Booligal 2
38 Waikerie 27W, 28W
39 Monash 1
40 Cooltong 1
41 North Renmark 1
42 Berri North 1
43 Berri South 1
44 Company Bore 1
45 Vic.D.M. Olney 1
46 Sunset 1
47 Morkalla 1
48 Lake Victoria 1
49 BMR Wild Dog 1
50 BMR Bramah 1
51 BMR Cumbung Swamp 1
52 Loxton 2
53 Loxton 1
54 Nadda 1
55 Mildura West 2
56 Mildura West 1
57 BMR Euston 1
58 Tol Tol
59 Robinvale 1
60 Vic.D.M. Geera 1
61 Balranald 1
62 BMR Kyalite 1
63 BMR Perekerton 1
64 BMR Tchelery 1
65 Hay 1
66 Killendoo 1
67 D.M. Morton 1
68 D.M. Bundoona 1
69 Tailem Bend 1
70 Pinnaroo 1
71 Gunamalary 1
72 BMR Piangil West 2
73 Bundy 1
74 D.M. Wood 1
75 D.M. Bundure 1
76 Jerilderie 1
77 Urana 1
78 Lake Cullival 1
79 Kiki Bore
80 Coonalpyn 1
81 Shaugh Bore
82 Vic.D.M. Meram 10
83 Keith 1
84 Vic.D.M. Warraquil 3
85 Vic.D.M. Yellangip 1
86 Calivil 2 Bore
87 Vic.D.M. Echuca North 1
88 Overland Corner 1

19/A/277

Fig. 23. Location of petroleum exploration wells and major stratigraphic bores; distribution of Upper Carboniferous – Lower Permian, Upper Permian, Mid-Triassic and Lower Cretaceous infrabasins beneath Cainozoic Murray Basin.

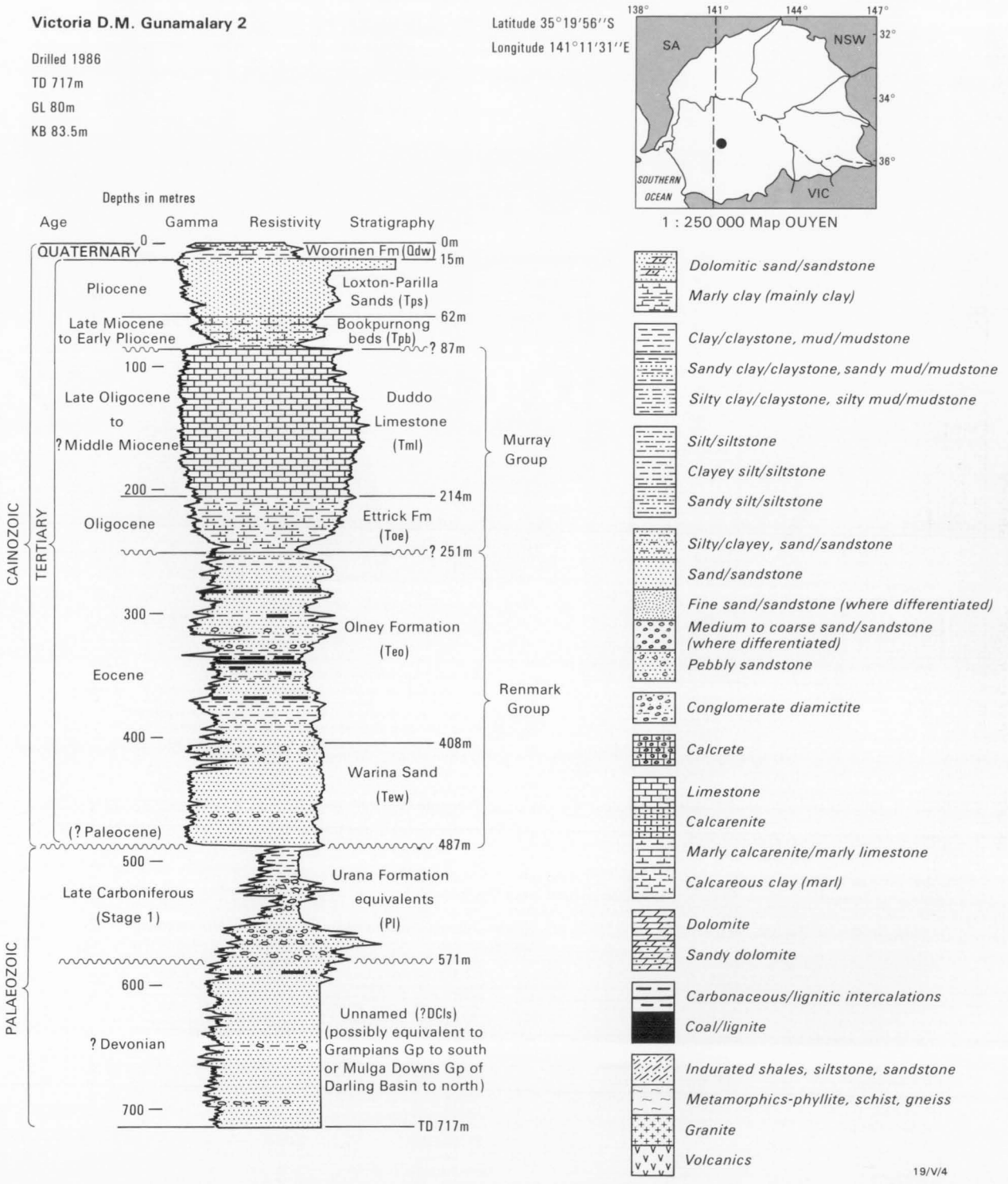


Fig. 24. Lithology log of Vic. D.M. Gunamalary No. 2 (based on Orth, 1986); symbols shown on lithology reference (and combinations of these symbols) apply to all following figures, except where indicated.

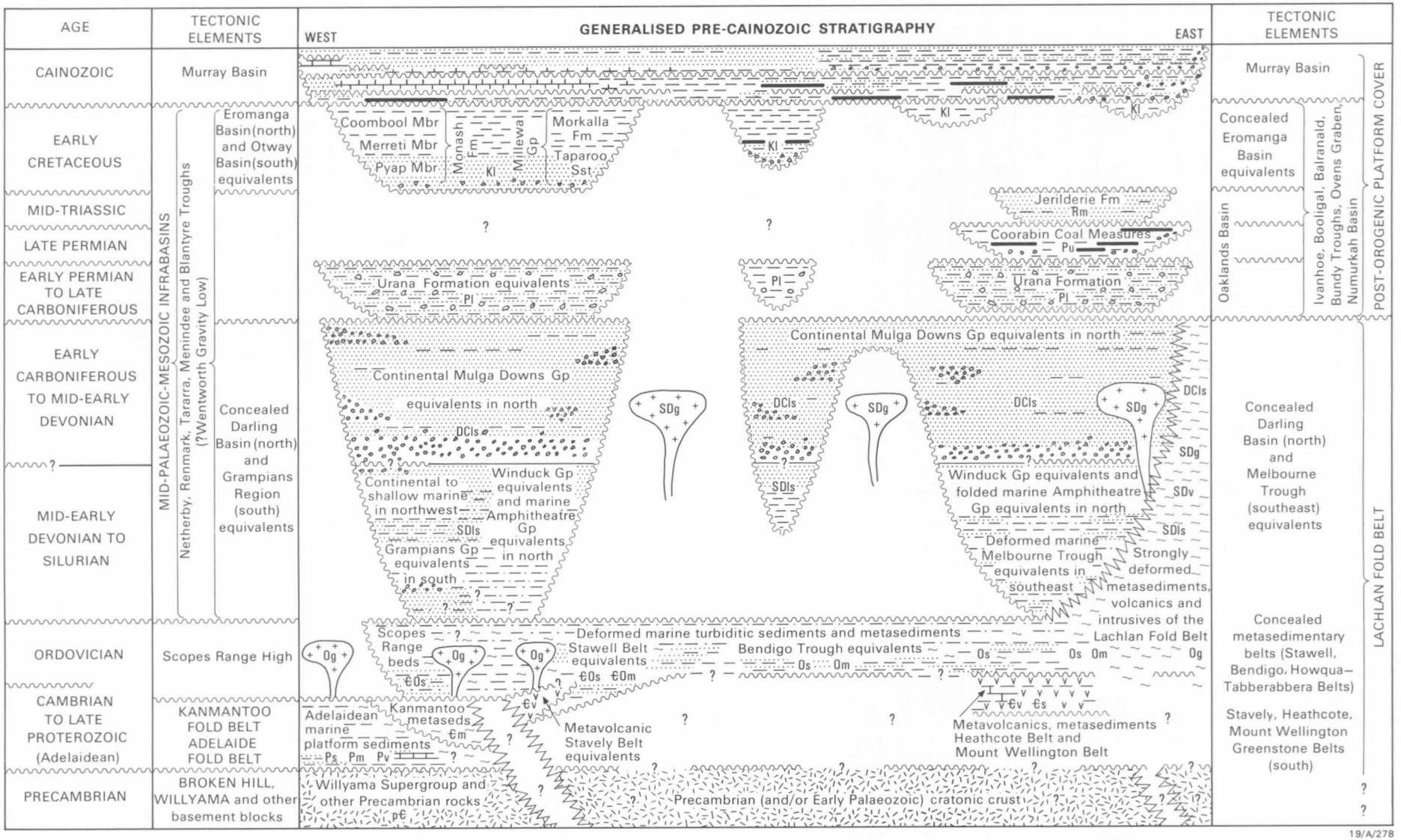


Fig. 25. Generalised pre-Cainozoic stratigraphy of infrabasins and tectonic elements underlying the Cainozoic Murray Basin.

sedimentary rocks have been interpreted from recent seismic surveys (e.g. Vale, 1986). The presence of such Devonian sedimentary rocks has been confirmed by boreholes in most of the northern troughs, but is less certain beneath the southwestern Murray Basin. However, magnetic imagery and Bouguer gravity anomalies (see Fig. 162; Plates 15, 16, 17) suggest that sediments similar to those of the Tararra and Renmark Troughs possibly extend to the southeast, towards outcrop of similar sedimentary rocks in the Grampians region (Figs 19, 23). If present, they are confined in distribution to small trough-like features, such as the Netherby Trough, few of which have been tested by drilling. To date, only one stratigraphic bore – Vic. D.M. Gunamalary No.2 (Fig. 24; Orth, 1986) – has encountered a possible Devonian succession in this southern area.

On the basis of correlation with the Darling Basin succession to the northeast and the Melbourne Trough and Grampians areas of the Lachlan Fold Belt to the south, the thick, predominantly Devonian, succession concealed beneath the western Murray Basin can tentatively be divided into two major sequences (Fig. 25) comprising a lower unit of predominantly fine-grained Lower Devonian marine and minor non-marine rocks, and an upper unit of coarse-grained, Devonian to Lower Carboniferous fluvio-lacustrine sedimentary rocks.

Lower Devonian sequence

The Lower Devonian sequence crops out in breached and faulted anticlinal cores in low hills to the north of the basin, but only four wells – NSW Oil & Gas Mount Emu No.1, North Star Ivanhoe No.1, NSW Oil & Gas Poopelloe Lake No.1, and Texam Berangabah No.1 – and one stratigraphic bore – BMR Ivanhoe No.1 – have encountered Lower Devonian marine sediments beneath the northwestern Murray Basin (Evans, 1977; Brown & others, 1982). In addition, probable Lower Devonian sediments were encountered by North Star Dolmoreve No.1 beneath the northwest Riverine Plain. No Silurian rocks have been identified, however, based on seismic evidence, Evans (1977) suggested that the lower sequence consists of up to 4 km of thinly bedded ?Upper Silurian to mid-Lower Devonian marine siltstone, shale, and minor sandstone (SDls – equivalent to the deeper-water turbiditic sediments of the Amphitheatre Group of the Cobar Supergroup of the Darling Basin – Baker & others, 1975; Baker, 1978; Glen, 1979, 1982,a,b; Glen & others, 1985). In the top few hundred metres, the Lower Devonian marine sedimentary rocks of the Amphitheatre Group grade upwards into regressive shallow-marine sandstone and siltstone bodies (SDls – equivalent to the shallow-marine shelf sediments of the Winduck Group of the Cobar Supergroup of the Darling Basin – Glen, 1982a,b). These quartz-rich shelf sandstones are planar-laminated or cross-laminated and are distinguished from the overlying continental sands of the Mulga Downs Group by the presence of shelly faunas and *Skolithos*-type burrows. The shell debris consists of bivalves, brachiopods, crinoids, tentactulites, and includes the index fossil *Howellella jaqueti*. Correlative, thick, moderately deformed, deeper-water marine sedimentary rocks of the Melbourne Trough to the southeast of the Murray Basin also grade up-sequence into Lower Devonian shallow-marine sandstone (VandenBerg & others, 1976; Garratt, 1983; VandenBerg, 1988).

NSW Oil & Gas Mount Emu No.1 (Fig. 26; Haskell & Wiltshire, 1970) was located in the Blantyre Trough and encountered 695 m (756 m to T.D. 1450 m) of Lower Devonian grey marine siltstone, sandstone, and minor oolitic, fossiliferous limestone.

NSW Oil & Gas Poopelloe Lake No.1 (Wiltshire, 1970) is located on an up-faulted segment of the central Lake Poopelloe Trough, at McCullochs Range (Fig. 22) to the north of the Murray Basin. The well encountered a thick Lower Devonian sequence of 708 m (17 m to T.D. 725 m) of grey shale, siltstone, and minor sandstone. The uppermost 80 m was weathered, while the deeper sections showed texture alteration associated with deep burial.

Texam Berangabah No.1 (Fig. 22; Ranneft, 1968) was drilled on the southeastern flank of the Lake Poopelloe Trough, and intersected 448 m of Lower to Middle Devonian, medium to dark-grey shaly siltstone with brachiopods. Minor interbeds of very fine-grained sandstone and micritic limestone were also encountered. BMR Ivanhoe No.1 (Fig. 22; Passmore, 1981) was drilled adjacent to the Berangabah No.1 site and continuously cored 301 m (4 m to T.D. 305 m) of grey bioturbated fossiliferous marine siltstone (Fig. 19), with increasing amounts of interbedded black shale towards the base. The sequence occurs towards the top of the Amphitheatre Group and contains an abundant and diverse fauna of articulate brachiopods (including *Howellella jaqueti*), ostracods, tentaculitids, gastropods, lamellibranchs, bryozoans, and conodonts – all of which indicate a Lochovian to Early Pragian age (Jones & others, 1981).

North Star Ivanhoe No.1 was drilled within the

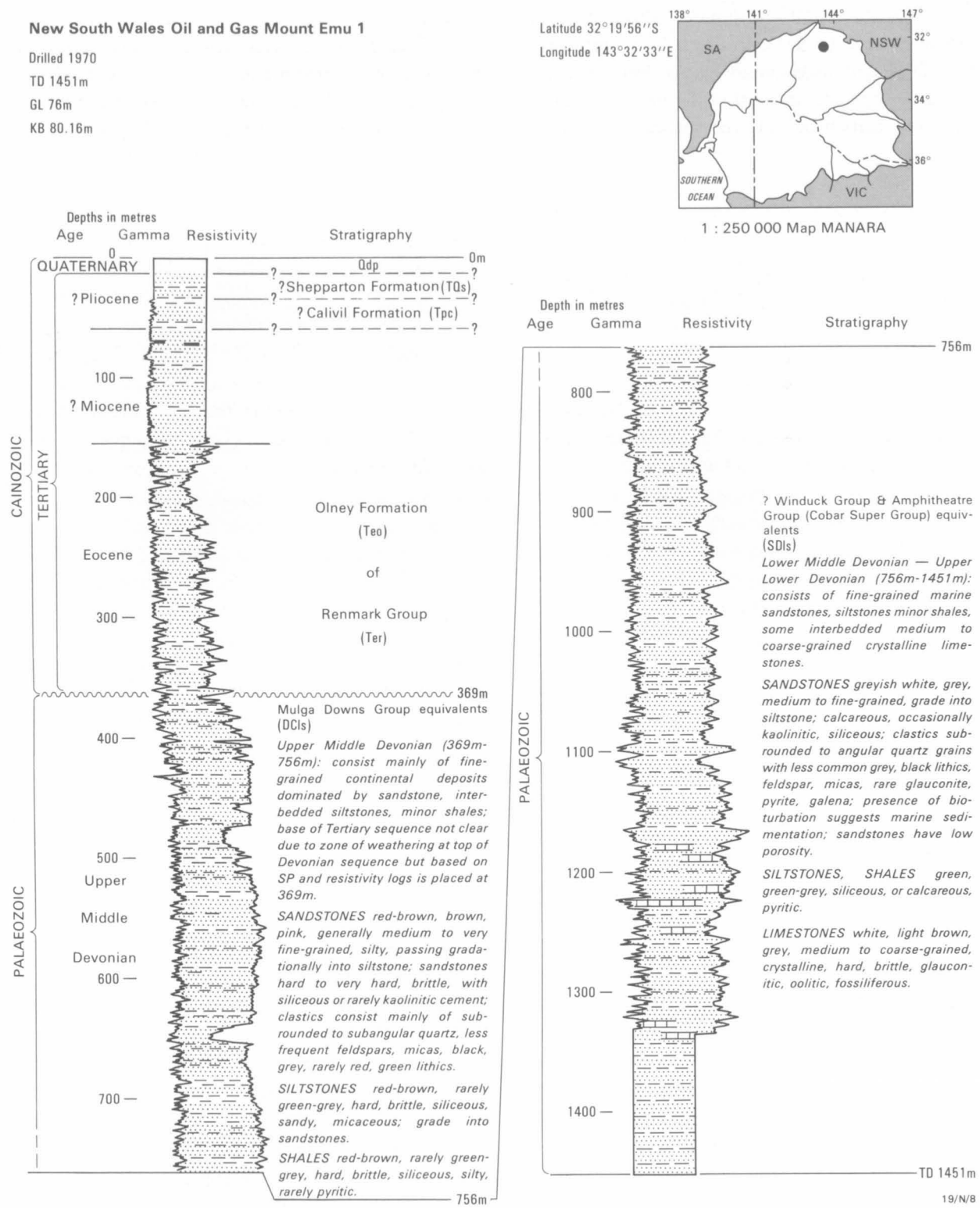


Fig. 26. Lithology log of N.S.W. Oil & Gas Mount Emu No. 1 (based on Planet Exploration well completion report by Haskell & Wiltshire, 1970).

TABLE 3. PETROLEUM EXPLORATION WELLS WHICH HAVE ENCOUNTERED DEVONIAN – LOWER CARBONIFEROUS ROCKS

Well	*Depth (m)*	*Thickness (m)*	*see Fig.*	*Reference*
Claremont Avery No.1	495	255+	Fig. 29	Gorter (1986a)
Comserv Blackgate No.1	507	1425+	–	Sniffen (1985)
Mid-Eastern Blantyre No.1	302	1987+	Fig. 27	Campe & Cundill (1965)
NSW Oil & Gas Booligal No.1 & 2	293	518+	–	Haskell (1970a)
North Star Conoble No.1	183	69+	–	North Star (1962)
International Mining Cooltong No.1	1185	191+	–	Archer (1988)
Texam Dolmoreve No.1	323	148+	–	Ranneft (1967)
Esso Ennisvale No.1	920	311+	–	Lindsay (1983) & McMaugh (1984a)
North Star Holey Box No.1	228	113	–	Texam (1967)
Claremont Ironstone Tank No.1	480	125+	Fig. 29	Gorter (1986b)
A.P.E. Killendoo No.1	356	399+	Fig. 30	Haites & Stewart (1964)
Claremont Kopi Plain No.1	752	793+	Fig. 29	Gorter (1986c)
NSW Oil & Gas Mount Emu No.1	369	1082+	Fig. 26	Haskell & Wiltshire (1970)
Esso Nulla Nulla No.1	1062	57+	–	Lindsay (1984) & McMaugh (1984b)
Esso Pamamaroo No.1	679	116+	–	Moreton (1983) & McMaugh (1984c)
Esso Popiltah No.1	940	63+	–	Archibold (1984) & McMaugh (1984d)
A.O.G. Tararra No.1	907	1028+	Fig. 28	Boyd & Heisler (1967)

gravity-defined Ivanhoe Trough (Figs 22, 23) and encountered 178 m (488 m to T.D. 666 m) of Lower Devonian calcareous siltstone and shale with traces of pyrite (see Fig. 30; Brundall, 1964).

Texam Dolmoreve No.1 (Ranneft, 1967) encountered 148 m (323 m to T.D. 471 m) of slightly metamorphosed sandstone, siltstone, shale and slate of uncertain but possible Early Devonian age (Sniffen, 1985).

As discussed by Brown & others (1982), the presence of Lower Devonian marine clastics has only been unequivocally established in areas east of the Lake Wintlow gravity high (Figs 20, 22), and only limited indications of the presence of marine Lower Devonian rocks have been recorded from the westernmost troughs. To the north of the Murray Basin, several hundred metres of coarse-grained continental redbeds, of possible Early Devonian age crop out in the Gnalta area (Fig. 22; Rose, 1974) and were encountered in Planet Bancannia South No.1 (location shown on Fig. 22; Baarda, 1968). In the Gnalta area, Strusz (1966) reported possible worm and trilobite tracks towards the top of the Lower Devonian sequence, suggesting the presence of marine rocks in adjacent concealed troughs to the southeast. In addition, marine rocks were interpreted in the Bancannia Trough (Fig. 22) from poorly preserved, possible marine or brackish water, algal microfloras of possible Early Devonian age in the basal Devonian section in Planet Bancannia South No.1 (Baarda, 1968; Evans, 1977). Seismic profiles in the Bancannia Trough suggest the presence of a large prograding delta (Evans, 1977), presumably grading laterally into marine sediments, or alternatively large alluvial fans (P.R. Evans, personal communication, 1981). The presence of marine Lower Devonian in the Menindee Trough was postulated on the basis of seismic character correlation with the Bancannia Trough sequence. However, it now seems likely that the basal section in Planet Bancannia South No.1 is entirely a continental redbed sequence (Baarda, 1968) – although the redbed character of the Lower Devonian may in part reflect poor development of land plants in the Early Devonian. In summary, the presence of marine Lower Devonian sedimentary rocks has not yet been conclusively established in the westernmost troughs beneath the Murray Basin.

Devonian to Lower Carboniferous sequence

The upper sequence (Fig. 25) is thought to consist of several kilometres of block-faulted, broadly warped mid-Lower Devonian to Lower Carboniferous fluviatile and lacustrine sediments. These consist of coarse-grained, yellow or red sandstone, conglomerate, white or red siltstone, and minor red shale (DCls – equivalent to the Mulga Downs Group of the Darling Basin – Mulholland, 1940; Conolly *In* Packham, 1969; Webby, 1972; Glen, 1979, 1982a,b). Well-cemented Middle to Upper Devonian continental sandstone and conglomerate of this sequence crop out from beneath the northern Murray Basin to form the Manara Hills, Manfred and Darnick Ranges (Fig. 22). Glen (1982a,b) described the boundary between the Winduck Group and the overlying Mulga Downs Group as being characterised by general paraconformity, with local disconformity and angular unconformity.

The presence of thick sequences of mid-Lower to Upper Devonian continental clastics has been

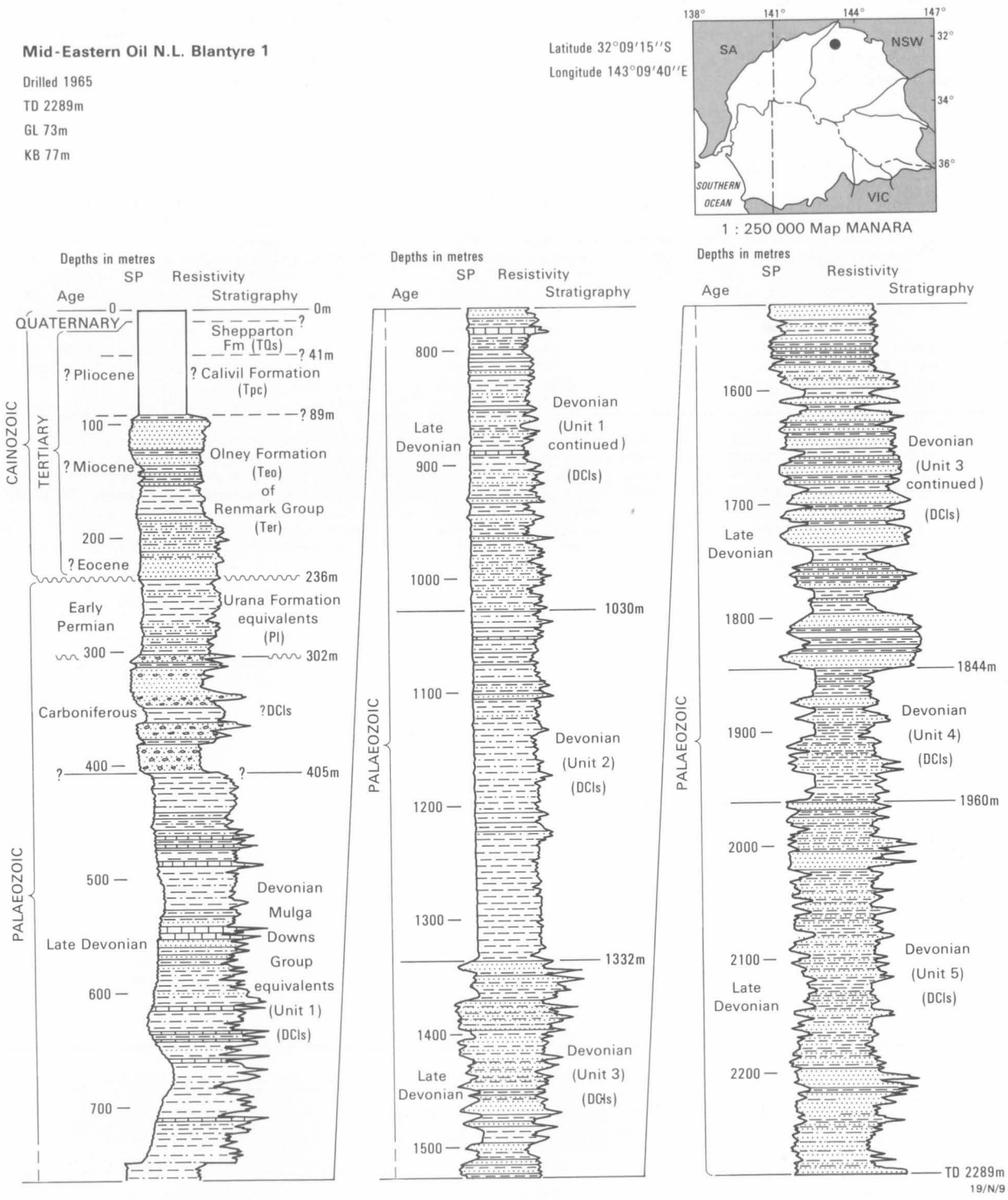


Fig. 27. Lithology log of Mid-Eastern Oil Blantyre No. 1 (based on Campe & Cundill, 1965) – see accompanying Table 4 for description of Units 1–5 of Devonian Mulga Downs Group; photo (a), on Table 4, shows core from Unit 1, and photo (b) a typical well-cemented quartz sandstone from Unit 5.

TABLE 4. UPPER DEVONIAN – LOWER CARBONIFEROUS ENCOUNTERED IN MID-EASTERN BLANTYRE No.1 (based on Campe & Cundill, 1965)

?Carboniferous (225 – 329 m) – see Fig. 27

Conglomerate: grey, poorly consolidated; quartz, quartzite, granitic and metamorphic pebbles in grey sandy clay matrix. Sandstone: very coarse-grained, conglomeratic; pebble sizes up to 5 cm. Minor interbeds of greyish slightly sandy shale.

Upper Devonian (405 – 2289 m)

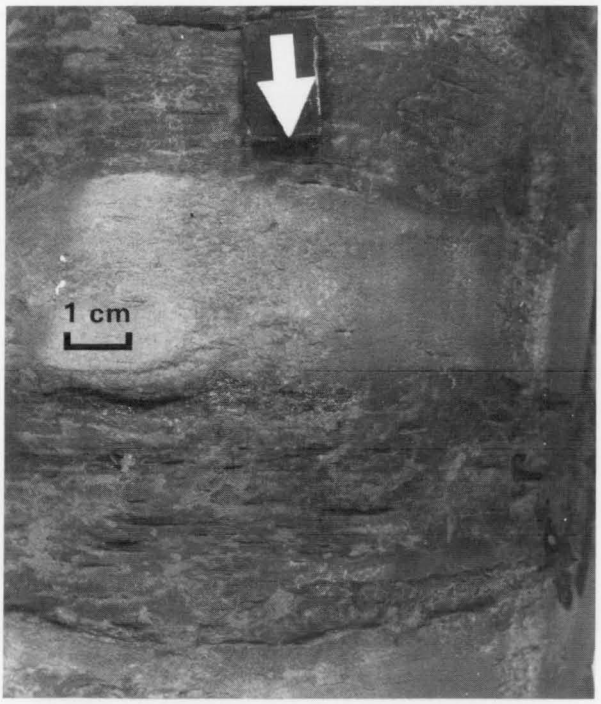
Unit 1 (405 – 1030 m) – Shale: grey, green, purple, red, mottled, occasionally yellow, moderately soft, slightly sandy, calcareous, micaceous, in places carbonaceous. Minor green waxy shale with slickensides. Siltstone: purple, brown, green, grey, firm, argillaceous, micaceous, occasionally calcareous, slightly sandy; rare oolites. Sandstone: red-brown, purple, light green-grey to white, very fine-grained, soft, friable, well-sorted, occasionally silty, argillaceous, slightly calcareous, carbonaceous. Limestone: brown to grey; Fe – Mg oolites in very fine, white, crystalline calcite matrix. Occurs as thin interbeds and stringers. Cores indicate well-developed bedding; slumps, current structures, cross-bedding; bands micaceous, carbonaceous, material; also oolites and rock fragments.

Unit 2 (1030 – 1332 m) – Shale: red, brown, grey, green, silty, occasionally sandy, slightly calcareous, slightly carbonaceous in places, fissile, splintery in part. Siltstone: red-brown, red, green, grey, grey-green, purplish grey, argillaceous, commonly sandy; in places grades to fine-grained calcareous sandstone. Minor sandstone: green, grey-brown, brown, red-brown, very fine-grained, hard, calcareous, argillaceous. Traces light-grey, brown, microcrystalline, oolitic limestone. Cores indicate depositional brecciation, mud cracks, mud pellets; 2 cm coquinite band of calcareous remains of worm Spirorbis in core 14.

Unit 3 (1332 – 1844 m) – Sandstone: very light-grey, green, red, brown, white, very fine-grained to coarse (mainly fine-grained); either hard, calcareous, siliceous, or soft semi-friable. Quartz rounded to subangular, clear, orange, occasionally green, fairly to well-sorted; quartz overgrowths; rare carbonaceous matter. Brown, green, clay pellets in siliceous, argillaceous, calcareous, occasionally kaolinitic matrix. Cores indicate massive, some well-bedded; minor cross-bedding; green banding due chlorite, micas. Shale: red-brown, green-grey, red, brown, purple, green-grey, black; contain some limestone nodules, spherulites, carbonaceous inclusions; minor pelletal shale; fish plates in core 19.

Unit 4 (1844 – 1960 m) – Shale: red, brown, green, grey, hard, firm, blocky, occasionally fissile, slightly calcareous, micaceous, occasionally siliceous, silty to sandy. Siltstone: red-brown, purple, brown, green, grey to brick red, generally sandy, occasionally grading to very fine-grained sandstone; slightly calcareous, micaceous, argillaceous, very slightly carbonaceous; firm, blocky. Sandstone: light-grey, light-green, white, light-brown, slightly argillaceous, silty; mainly fine to coarse-grained, fair to well-sorted, sub-angular to rounded. Varicoloured quartz, black, green mafics, occasional orange feldspars; in argillaceous, kaolinitic, calcareous, siliceous matrix. Thin grey, green banding due chlorite, mica; minor clay pellets also present. Possible fish spine.

Unit 5 (1960 – 2289 m) – Sandstone: light-grey, fine to medium-grained, kaolinitic, slightly siliceous; also white siliceous, medium to coarse-grained sandstone, and green sandstone. Consist of poorly to well-sorted, euhedral to rounded, varicoloured quartz, green chlorite, orange feldspar, black, green clay pellets, occasional mica, black mafics, trace gypsum; argillaceous, calcareous, siliceous matrix. Cores indicate massive, common cross-bedding. Inclusions of grey, green shales, fairly common clay pellets. Shale: brown, grey, green, blue-grey, hard, fissile or blocky, silty to sandy, slightly micaceous, calcareous, siliceous, locally bentonitic. Siltstone: brown, purple, red-grey, green, micaceous, siliceous, argillaceous, generally sandy, slightly calcareous, fissile or blocky, fairly hard. Contains rare oolites. Trace coal and microcrystalline limestone.



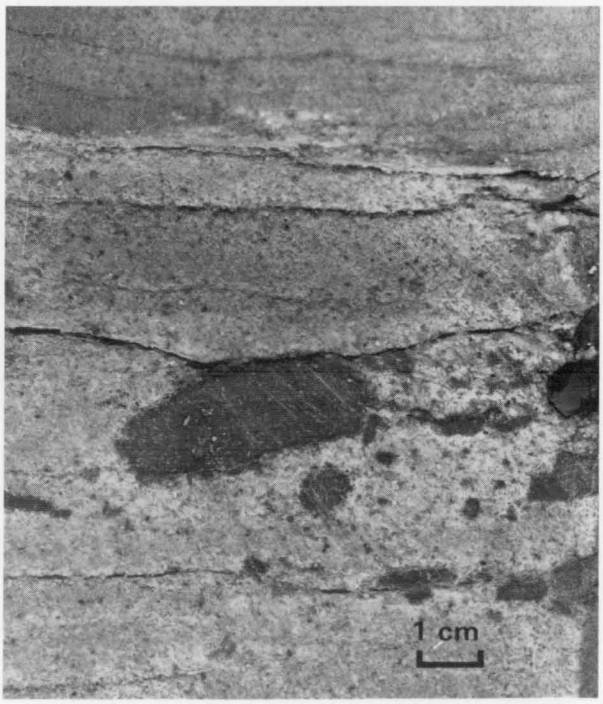


Table 4 – photo (a) shows core from Unit 1, and photo (b) a typical well-cemented quartz sandstone from Unit 5 – see Fig. 27.

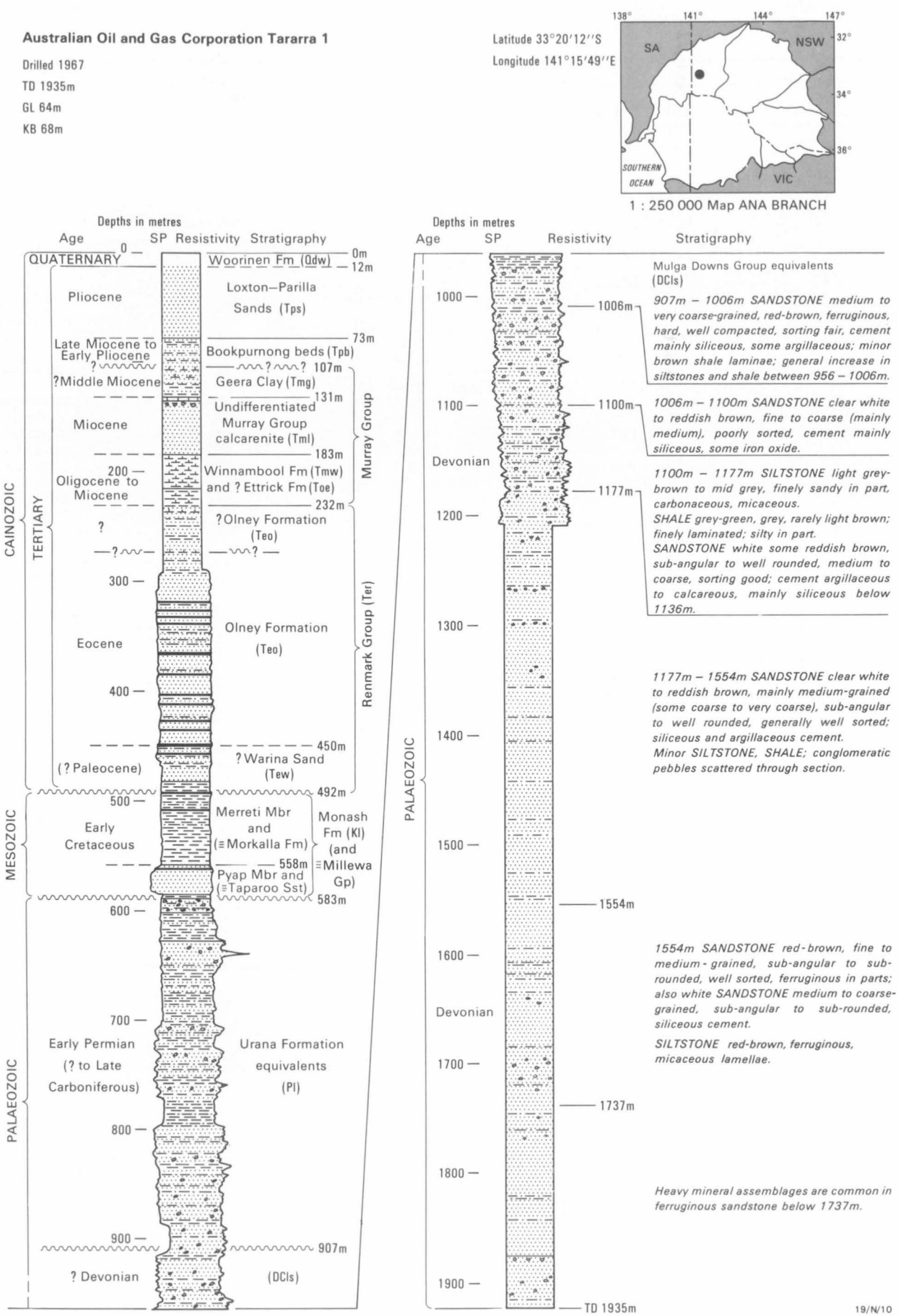
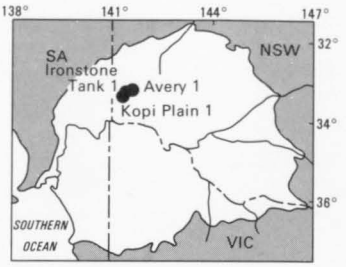


Fig. 28. Lithology log of Australian Oil & Gas Tararra No. 1 (based on Boyd & Heisler, 1967).

Claremont Petroleum Kopi Plain 1, Ironstone Tank 1 and Avery 1

Kopi Plain 1	Ironstone Tank 1	Avery 1
Drilled 1986	Drilled 1986	Drilled 1986
TD 1545m	TD 605m	TD 750m
GL 37m	GL 57m	GL 55m
KB 41m	KB 61m	KB 59m
Latitude 33°13′40″S	Latitude 33°07′39″S	Latitude 33°06′14″S
Longitude 141°16′07″E	Longitude 141°23′05″E	Longitude 141°27′14″E



1 : 250 000 Map ANA BRANCH

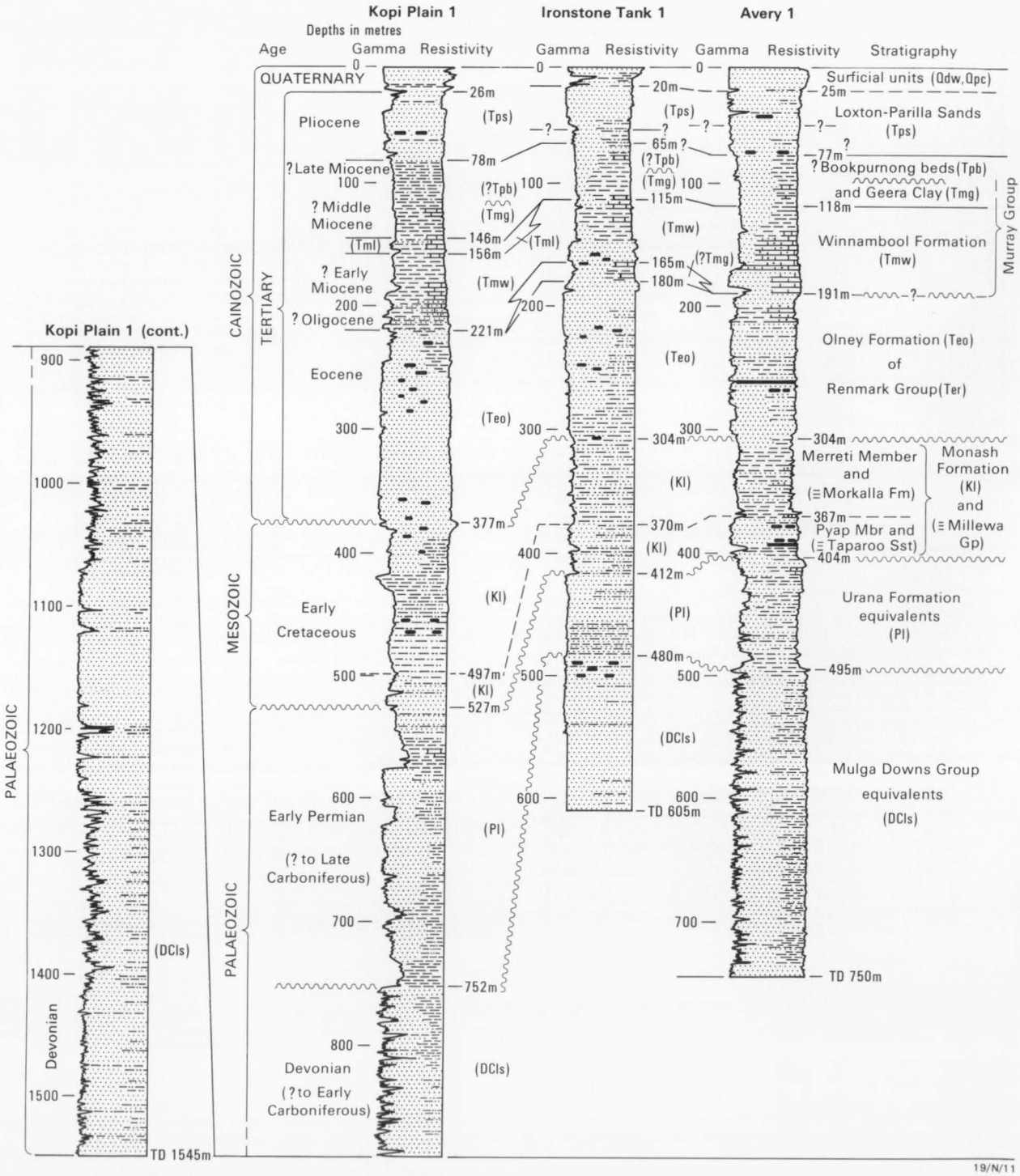


Fig. 29. Lithology logs of Claremont Kopi Plain No. 1, Ironstone Tank No. 1, and Avery No. 1 (based on Gorter, 1986a,b,c).

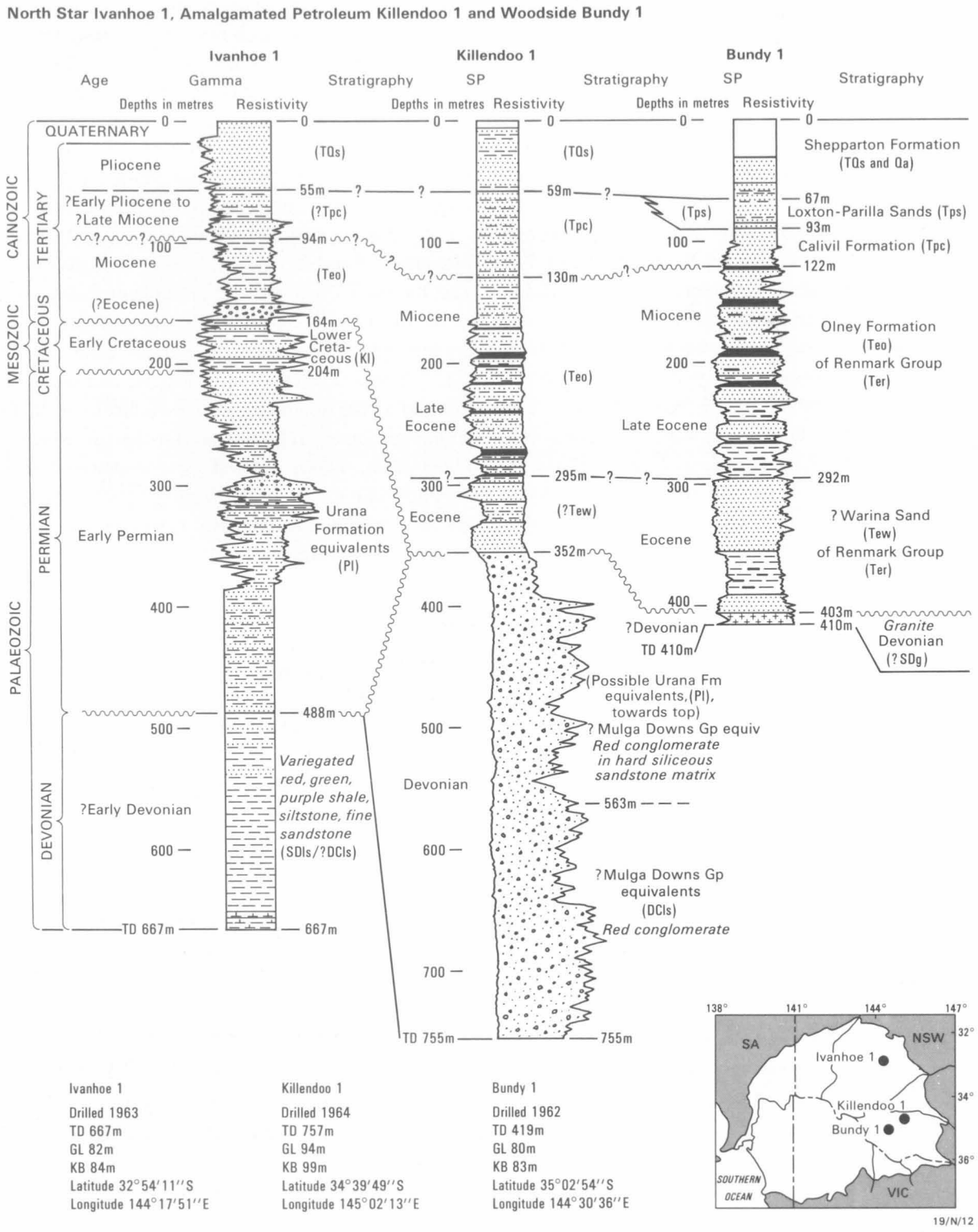


Fig. 30. Lithology logs of North Star Ivanhoe No. 1 (Brundall, 1964), Amalgamated Petroleum Killendoo No. 1 (Haites & Stewart, 1964), and Woodside Bundy No. 1 (Shiels, 1962).

confirmed in the west and north by several petroleum exploration wells and several water bores. Both Comserv Blackgate No.1 and Mid-Eastern Blantyre No.1 encountered a succession of nearly 2 km and failed to reach the bottom of the sequence (Table 3; Bembrick, 1974; Thornton, 1974, 1976; Sniffen, 1985; Brown & Stephenson, 1986). Comserv Blackgate No.1 (Sniffen, 1985), for example, drilled through 553 m of Upper Devonian silicified light red-brown to grey sandstone, with minor white to red claystone, shale and quartzose siltstone. From 1060 m to T.D. 1932 m, the well also encountered 872 m of Middle Devonian olive grey sandstone with minor interbeds of siltstone and shale. From 405 m to T.D. 2289 m, Mid-Eastern Blantyre No.1 penetrated a 1884 m thick sequence consisting of ?Carboniferous conglomerate over Devonian shale, siltstone and sandstone with minor limestone (Fig. 27, Table 4; Campe & Cundill, 1965). A representative section drilled by A.O.G. Tararra No.1 (1028 m, from 907 m to T.D. 1935 m; Boyd & Heisler, 1967) is shown on Figure 28. Claremont Kopi Plain No.1 (Fig. 29) entered a similar thick sequence at 752 m and remained within Devonian sandstone until T.D. at 1545 m. Other wells which have found Devonian continental sequences beneath the Murray Basin are listed on Table 3. In A.O.G. Wentworth No.1 a basal unit consisting of 8 m of sandy conglomerate was originally logged as Carboniferous–Permian (see Figs 33a, 39; Rose, 1962a), but Sniffen (1985) has suggested that the unit is possibly Devonian in age.

As discussed by Brown & others (1982), in the Menindee, Tararra, and Renmark Troughs to the west the thick Devonian succession is probably mainly continental. It may include correlatives of the predominantly non-marine, Devonian (and possibly older) quartz sandstone, red siltstone, and mudstone exposed at the southern margin of the basin in the Grampians area (Grampians Group of Spencer-Jones, 1976, 1988), as well as correlatives of the Darling Basin to the north. Wopfner (1970) reported the occurrence of dolomite (?lacustrine) in the Devonian of the Renmark Trough.

Upper Carboniferous to Cretaceous post-orogenic platform cover

Extensive but discontinuous remnants of Upper Carboniferous to Lower Permian glacio-marine and possible sub-glacial tillite deposits of the Urana Formation are preserved within several of the infrabasins underlying the Murray Basin (Figs 23, 25, 32). These sediments can be correlated with equivalent glacio-marine sedimentary rocks of the Cape Jervis beds exposed in the Fleurieu and Yorke Peninsulas, west of the Murray Basin in South Australia (Foster, 1974), and with other small outcrops of non-marine glacials exposed in the Victorian highlands to the south. The thickest sequence encountered to date is 888 m in A.O.G. Jerilderie No.1 (Fig. 31; Wright & Stuntz, 1963) beneath the southeastern Murray Basin in the Oaklands Basin (Fig. 32). In that basin, the Lower Permian sequence is disconformably overlain by a 70 m thick Upper Permian unit consisting of at least three disconformably stacked upward-fining cyclic fluvial sequences (Coorabin Coal Measures – Morgan, 1977a; Standing Committee on Coalfield Geology, 1976; Yoo, 1981a, 1982). Similar non-marine rocks of Late Permian age occur in the adjacent concealed Numurkah Basin region to the west of the Oaklands Basin, and equivalent rocks may possibly occur within other troughs elsewhere beneath the Murray Basin.

Triassic rocks have been identified only in the Oaklands Basin, where the Upper Permian sedimentary sequence is disconformably overlain by Mid-Triassic fluvial sediments of the Jerilderie Formation (Fig. 31; Morgan, 1977a). These Triassic rocks of the Oaklands Basin were previously thought to be of Palaeogene age because they are lithologically similar to basal Tertiary sands elsewhere in the basin, and hence Triassic rocks are possibly more widely distributed than is currently known.

No Jurassic sedimentary rocks have as yet been identified beneath the Murray Basin, but a small area of fossiliferous sandstone exposed near Neckarboo on IVANHOE contains abundant plant debris which has been dated as Jurassic (see IVANHOE 1:250 000 geological map – Bryan, 1968). Jurassic volcanics and possible sediments have also been identified in adjacent areas of southwestern Victoria, to the south of the Murray Basin (e.g. Spencer-Jones, 1956; Douglas, 1976, 1988). In addition, high-amplitude point-source magnetic anomalies beneath parts of the Murray Basin could be interpreted as narrow vertical pipe-like mafic or ultramafic bodies, some of which may prove to be Jurassic kimberlites similar to those described in the adjacent highlands by Ferguson & others (1979).

Extensive, but thin and discontinuous, remnants of fluviatile and shallow-marine Lower Cretaceous

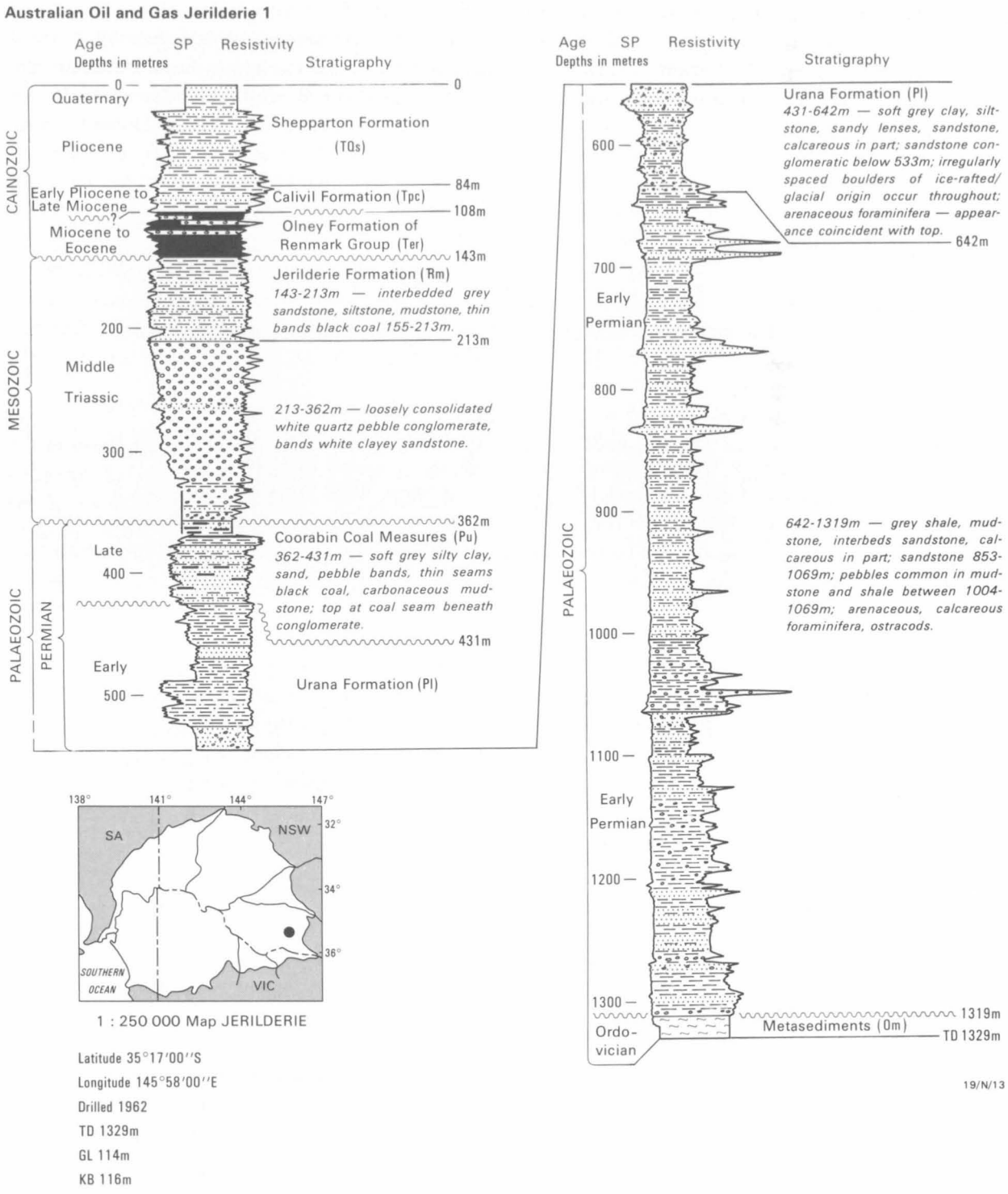


Fig. 31. Lithology log of Australian Oil & Gas Jerilderie No. 1 (based on Wright & Stuntz, 1963).

sedimentary rocks have been encountered by many bores drilled into troughs underlying the western and northern Murray Basin. These rocks can be correlated with those of the Eromanga Basin to the north. Cretaceous rocks have also been found by bores at the southern margin of the basin in southwest Victoria, but these are volcaniclastic and have been correlated with those of the Otway Basin to the south. Upper Cretaceous rocks have not been identified beneath the Murray Basin, although much of the Cainozoic succession is underlain by a white kaolinitic clay layer, thought to have formed during periods of regional weathering in the Upper Cretaceous. In addition, Macphail & Truswell (1989) identified a Late Cretaceous spore (latest Albian–Cenomanian) of unknowm source, within Late Eocene sediments in the northwest of the Murray Basin.

Upper Carboniferous–Lower Permian, Upper Permian, and Triassic (by P.E. O'Brien)

Upper Palaeozoic sediments beneath the Murray Basin (Fig. 32) consist of two units: the Upper Carboniferous to Lower Permian Urana Formation and Upper Permian Coorabin Coal Measures (Fig. 25; Thornton, 1974; O'Brien, 1981, 1986; Yoo, 1982). They are overlain in the Ovens Graben by the Triassic Jerilderie Formation (Standing Committee on Coalfield Geology, 1976).

Unit: Urana Formation
Age: Late Carboniferous to Early Permian (Stage 1, 2 and 3 microfloras of Kemp & others, 1977)
Map symbol: Pl

Lithologies. Drill cores from the Urana Formation consist of the following facies (Table 5):

Diamictite facies. Facies D1 – fine-grained diamictite with a clayey silt matrix surrounding medium to coarse sand and scattered pebbles (Fig. 34). Facies D1 forms massive to faintly laminated beds from a few centimetres to over 20 cm thick. Many beds have gradational upper and lower boundaries. Facies D1 is depleted in fine sand and coarse silt relative to fine tillites from central Victoria.

Facies D2 – diamictite with a similar grain-size distribution to some silty subglacial tillites in central Victoria. Beds of Facies D2 range from 5 cm to over 20 cm thick and are massive. The contacts between beds of Facies D2 and other facies are sharp and irregular with small flame structures along the contact. Fragments of intrabasinal mudstone and diamictite are present in some cores of Facies D2 (Fig. 34).

Facies D3 – laminated claystone with abundant coarse sand grains and scattered pebbles (Fig. 33a). Many pebbles are over-sized compared to the laminae in which they rest. Facies D3 beds are up to 5 cm thick and have gradational boundaries with overlying and underlying beds of mudstone facies and Facies D1.

Mudstone facies. Facies M1 – massive to poorly laminated siltstone with minor amounts of fine sand and rare pebbles. Beds range from 10 cm to over 30 cm thick. Most cores of Facies M1 are massive, but a few from Jerilderie No.1 show faint, discontinuous horizontal laminae and burrowed horizons. Foraminifera are present in some cores. Common features of this facies are red-brown, ferruginous patches and concretions.

Facies M2 – consists of graded siltstone and claystone couplets from 2 mm to 3 cm thick (Figs 33b,c). The base of each graded unit is sharp and the lower siltstone part of the graded unit grades continuously into the overlying claystone. Some cores of this facies contain scattered coarse sand grains, particularly in the claystone part of the graded units. Figure 33c shows a sandy mudstone clast within a graded unit. These clasts have a framework of medium sand set in a mud matrix and have diffuse boundaries with the surrounding sediment. Facies M2 is commonly deformed, either by clay beds intruding the bottom of the siltstone and breaking it into boudins (Fig. 33b) or by mixing of the interbeds accompanied by small recumbent folding. This mixing and folding may affect up to 40 cm of sediments.

Facies M3 – consists of thin mudstone, graded and ungraded fine sandstone beds, and rare sandstone beds consisting of single ripple cross-sets 1 cm thick. These interbeds are mostly less than 1 cm thick.

Sandstone facies. Facies S1 – poorly-sorted, silty coarse sandstone with rare pebbles and mud clasts. It forms beds from 1.5 cm thick (Fig. 21) to over 30 cm thick. This facies is massive in most cores, though some display faint horizontal laminae and the thin bed in Figure 21 is normally graded over the upper 0.5 cm.

Facies S2 – white, massive, well-sorted medium sandstone, commonly with a carbonate cement.

Facies S3 – yellow fine sandstone which has parallel

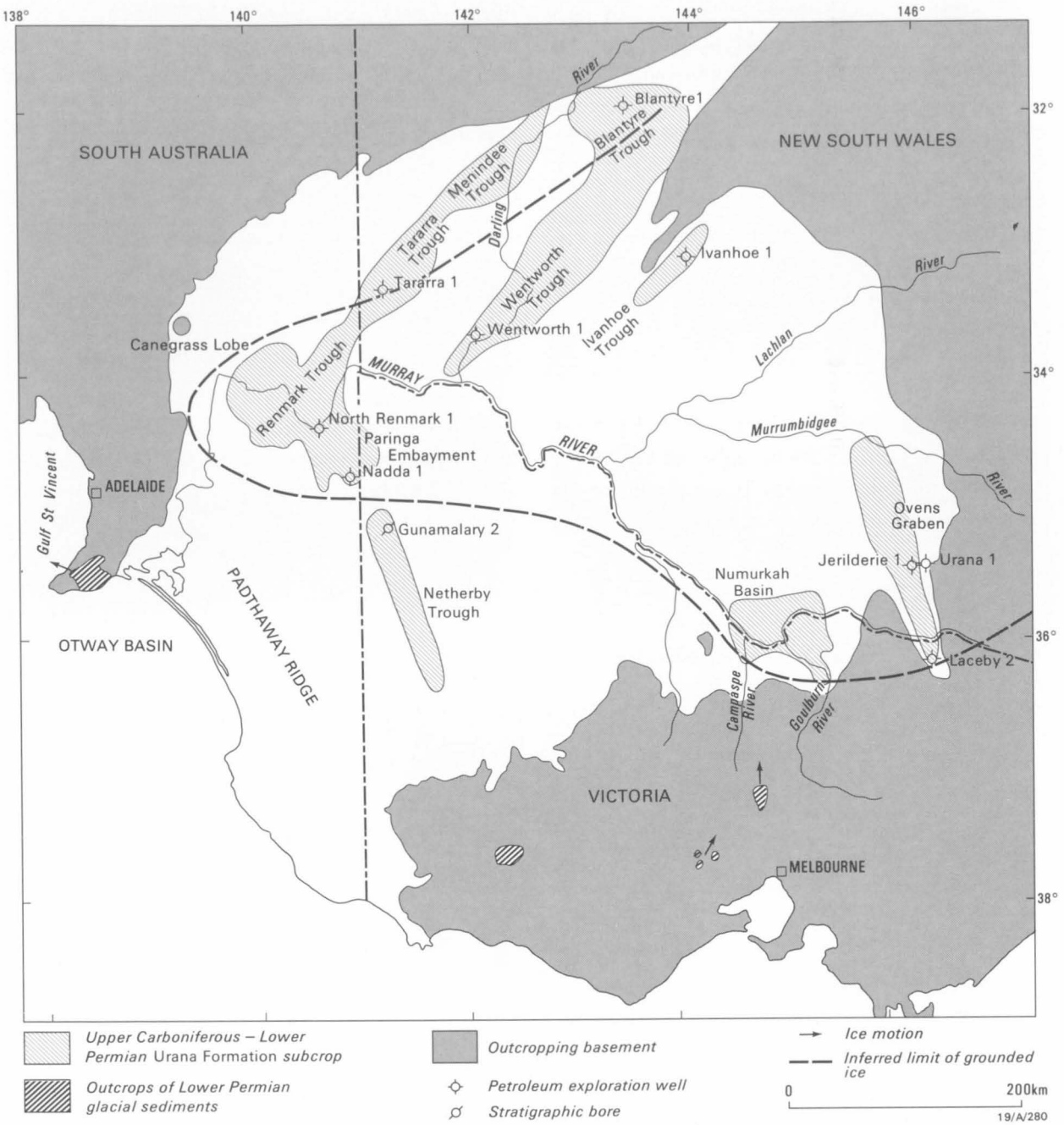


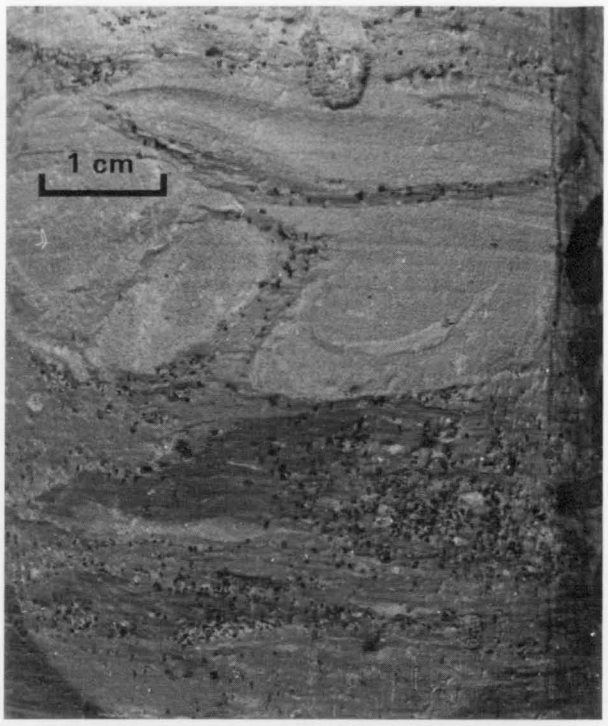
Fig. 32. Infrabasins beneath the Murray Basin containing Permo-Carboniferous and Triassic sediments (modified after O'Brien, 1986).

laminae or ripple cross-bedding. Some cores have fine fragments of organic matter scattered along laminae. Facies S3 beds range from 1 cm to over 5 cm thick.

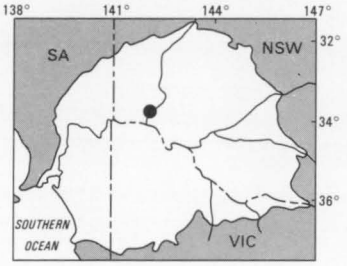
Conglomerate. A few wells penetrated sandy boulder conglomerate. This facies is clast-supported with up to 20% coarse sand matrix and framework clasts up to 15 cm in diameter. One core has interbeds of coarse sandstone up to 5 cm thick in the conglomerate.

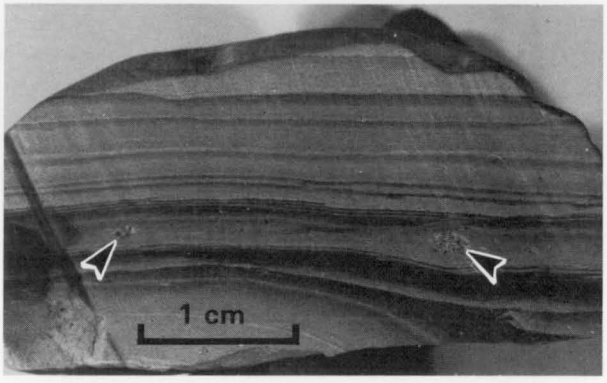
Other lithologies. Gorter (1986a,b,c) has recorded the presence of limestone and coal in cuttings from three wells drilled in the Tararra Trough (Claremont Avery No.1, Kopi Plain No.1, and Ironstone Tank No.1; Fig. 29). The limestone cuttings consist of white to brown, micritic limestone which appears as thin, sharp, high-velocity peaks on the sonic logs. The limestone is interbedded with mudstone facies. The coal cuttings are black, dull to subvitreous to brown and earthy (Gorter, 1986a,b,c). Their relationship to other facies is difficult to determine, as there is no clear evidence of coal beds on the geophysical logs

(a)



(b)





(c)

Fig. 33. Core material from Lower Permian Urana Formation equivalents, in Australian Oil & Gas Wentworth No. 1: (a) Facies D3 – diamictite formed by ice-rafting of sand and gravel into clay – from core 6 at 613 m; (b) Facies M2 has suffered soft-sediment deformation; light-grey siltstone forms load casts separated by flames of underlying claystone; darker claystone contains abundant ice-rafted coarse sand – from core 5 at 549 m; (c) Facies M2 – graded siltstone and claystone beds with ice-rafted till pellets indicated by arrows – from core 4 at 539 m.

of the holes.

Distribution and thickness. The Urana Formation does not crop out. It is present in the Renmark Trough, the Canegrass Lobe, the Paringa Embayment, the Tararra, Menindee, Wentworth, Ivanhoe, Blantyre and Netherby Troughs, the Numurkah Basin, and the Ovens Graben (Fig. 32, Thornton, 1976; O'Brien, 1981). The formation has also been identified in bores beneath the Loddon Valley (Macumber, 1978d). The maximum known thickness of the Urana Formation is 888 m in A.O.G. Jerilderie No.1 in the Ovens Graben (Wright & Stuntz, 1963). Similar thicknesses may be present in the Renmark Trough (Thornton, 1974).

Geometry. The Urana Formation is only gently deformed (Palmer, 1977; Yoo, 1982). Where the infra-basins are fault-bounded, the Urana Formation is truncated by the boundary faults but it laps onto basement in places where there are no faults (Thornton, 1974).

Palaeontology and age evidence. The Urana Formation contains arenaceous foraminifera, mostly of the

TABLE 5. FACIES OF URANA FORMATION

Facies	*Lithology*	*Interpretation*
D1	Fine diamictite; gradational bed boundaries	Compound paratillite
D2	Diamictite; sharp bed boundaries; mud clasts	Sediment gravity-flow deposits or subglacial tillite
D3	Fine diamictite; claystone matrix; thin, gradational bedding	Compound paratillite
M1	Massive to poorly laminated mudstone	Settling of suspended mud
M2	Interbedded mudstone & fine sandstone	Alternating deposition by currents & settling of suspended mud
S1	Poorly sorted, silty coarse sandstone; massive to faintly laminated	Rapid deposition by currents – possibly high density turbidity currents
S2	Massive medium sandstone	Current deposition
S3	Parallel laminated to ripple cross-laminated fine sandstone	Current deposition
Conglom.	Coarse sandy conglomerate	Deposition from high energy currents in deltas, sub-aqueous outwash fans & beaches

Section	*D1*	*D2*	*D3*	*M1*	*M2*	*M3*	*S1*	*S2*	*S3*	*Congl.*	*Microflora*
Nadda–1	2	–	–	–	2	–	2	–	–	–	Stage 2
North Renmark–1	–	–	–	–	2	2	–	–	–	2	Stage 2
Wentworth–1	–	–	2	–	2	–	1	–	–	1	Stage 2
Tararra–1	–	2	–	2	–	–	–	–	?2	–	Stage 2
Blantyre–1	–	2	–	–	–	–	–	–	–	–	–
Laceby–2	2	2	–	1	–	–	2	–	1	1	–
Numurkah Trough	2	2	–	2	–	–	–	–	–	–	Stages 2 & 3
Jerilderie–1	2	1	–	2	–	–	2	2	2	–	Stage 3

Facies assemblages based on O'Brien (1986)
2 indicates major constituent of section; 1 indicates a minor constituent; palynology from Ludbrook (1962b, 1963c), Derrington & Anderson (1970), Boyd & Heisler (1967), McLeod (1977, 1978, 1979), and Morgan (1975b).

genera *Ammodiscus* and *Hyperammina* (Crespin, 1958; Ludbrook, 1967b; Scheibnerova, 1980). Terpstra (1963) also reports some unidentified calcareous foraminifera and ostracods. Palynomorphs are also present.

The Urana Formation comprises the Stage 1, 2 and Stage 3 microfloras of Kemp & others (1977). Stage 2 and 3 microfloras have been found in most sections examined for palynomorphs (O'Brien, 1986), but the discovery of a Stage 1 microflora in a stratigraphic hole, Vic. D.M. Gunamalary-2 (Helby *in* Orth, 1986), suggests that older parts of the Urana Formation may be more common than has been thought. Kemp & others (1977) regard Stage 1 and 2 as Late Carboniferous, presumably Gzhelian, and Stage 3 as Early Permian, covering both the Asselian and Sakmarian, whereas Archbold (1982) regards both stages as Early Permian with Stage 2 mostly Asselian and Stage 3 mostly Sakmarian.

Characteristics. The Urana Formation is distinguishable from overlying units by the presence of ice-rafted coarse sand, granules and pebbles in much of the mudstone, as well as by the presence of diamictite. It is also characterised by a greater degree of induration in comparison with overlying sediments. Sedimentary rocks beneath the Urana Formation are even more indurated, and are often metamorphosed and deformed, with steeply dipping cleavage.

Depositional environments. Diamictite. The Urana Formation consits of an array of poorly sorted, pebbly facies similar to the contemporaneous glacial sediments which crop out south of the Murray Basin, but they have, in places, marine fossils. Therefore, they are the glaciomarine equivalents of the terrestrial glacial sequences of central and northeastern Victoria and southeastern South Australia (Crowell & Frakes, 1971a,b; O'Brien, 1986, 1989).

Three different types of diamictite are present (O'Brien, 1986). Facies D3 (Table 5) is a compound paratillite formed by rafting of the coarse-grained fraction into an area of clay deposition. Facies D1 is also a compound paratillite resulting from rafting and dropping of sand and pebbles into silts. It probably represents higher rates of ice-rafted sediment deposition than D3 because the sand fraction is much more abundant. Massive, tillite-like Facies D2, however, has two possible origins: either it may have been deposited by gravity flow, or may consist of subglacial tillites deposited by ice advancing out into the basin. Subglacial tillites may be present along the southern margins of the Numurkah Basin and the Ovens Graben and in Mideastern Tararra No.1 and A.O.G. Blantyre No.1, but the cores of Facies D2

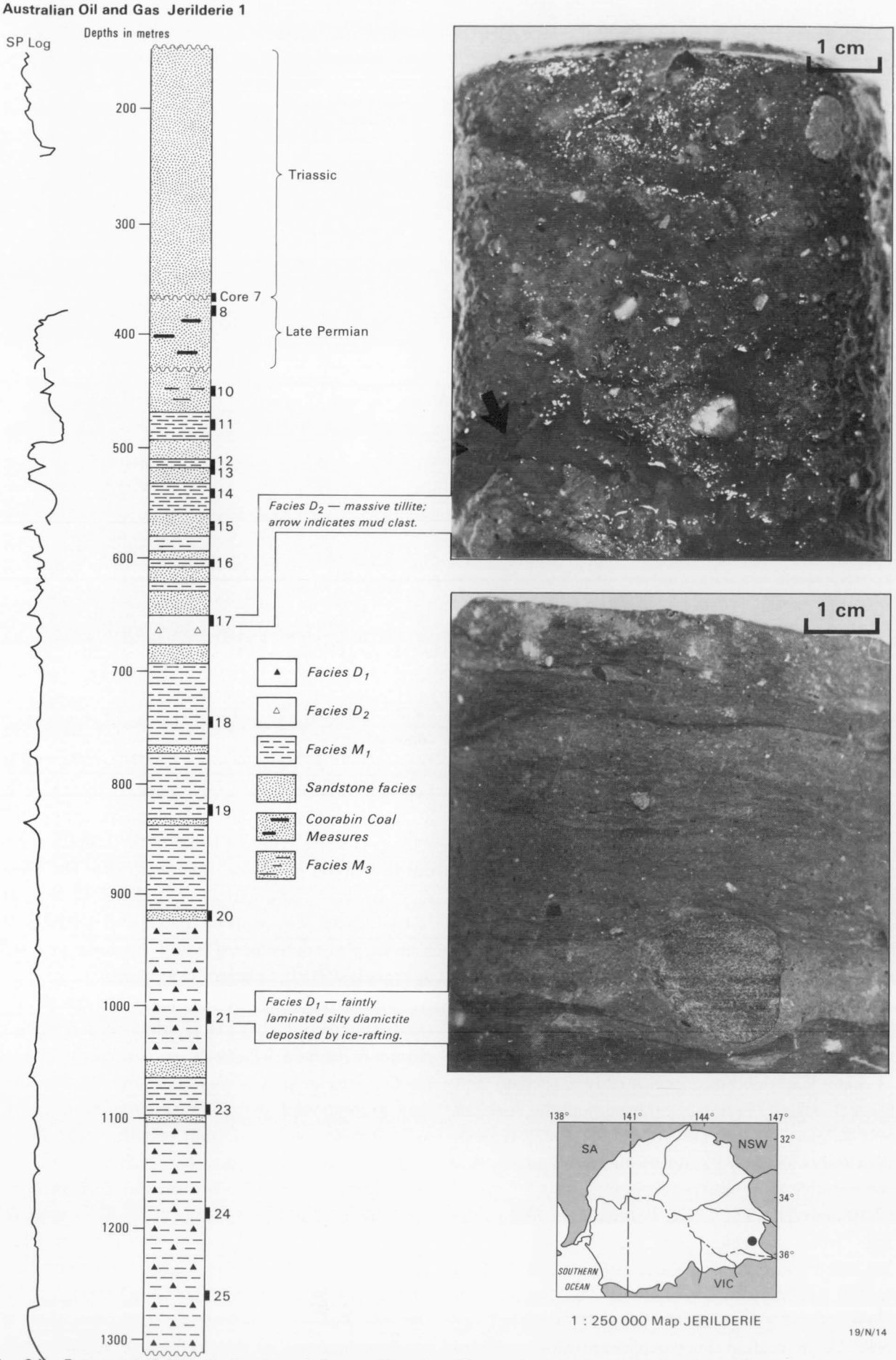


Fig. 34. Interpreted lithofacies log of Lower Permian Urana Formation in A.O.G. Jerilderie No. 1; core samples show Facies D1, D2 (see accompanying text for explanation).

recovered from the other petroleum wells are probably sediment gravity flows, because many are thin and contain mud-clasts probably ripped up from mud over which the flows moved.

Mudstone. Settling of fine particles from suspension produced the massive Facies M1 and the claystone parts of M2 and M3, but the graded siltstone parts of M2 and the siltstone and sandstone laminae of Facies M3 indicate deposition by currents. Facies M2 exhibits grading without clear separation of silt and clay parts of the graded beds. This sort of grading is typical of rhythmites deposited in marine environments, where clay minerals flocculate and deposit with part of the silt fraction (Duff & others, 1967). Currents of three possible origins may have deposited the graded beds of Facies M2: density currents produced by meltwater inflow moving as underflows or overflows (Kuenen, 1951); turbidity currents generated by slumping of the sea floor (Carey & Ahmad, 1961); or currents generated by katabatic winds flowing off a large ice mass (Gilbert & Shaw, 1981). The scattered coarse grains in Facies M1, M2, and M3 were ice-rafted into place. In Facies M2, the development of flame structures and soft-sediment boudins, results from loading of clay by rapid deposition of silt, causing simple clay-into-silt intrusion, but the complex mixing of siltstone and claystone with recumbent folding of laminae probably results from slumping of the seafloor.

The coal cuttings observed by Gorter (1986a,b,c) may represent dispersed wood fragments deposited with these facies. The bioclastic limestone beds interbedded with mudstone facies in some sequences (Gorter, 1986a,b,c) may have accumulated on the sea floor during periods of low sediment input or minor erosion.

Sandstone. The sandstone facies are difficult to interpret with any certainty because of the small cores available. The poor sorting of Facies S1 suggests rapid deposition from currents carrying a wide range of particle size in suspension (Stewart & La Marche, 1967). These currents were powerful enough to erode mud clasts from underlying sediment. The other two sandstone facies are finer and better sorted than Facies S1 suggesting more consistent currents than those responsible for Facies S1. In a glaciomarine setting, sandstone might be deposited as part of subaqueous outwash fans or deltas (Banerjee & McDonald, 1975), by currents sorting the sea bed or by slump-generated turbidity currents. Sandstone facies in the upper part of A.O.G. Jerilderie No.1 give an S.P. log signature, which suggests a coarsening-up, deltaic sequence (Fig. 34), but elsewhere in the basin evidence as to the origins of the sandstone is lacking.

Conglomerate. The small size of the cores taken in conglomerate makes it difficult to draw any conclusions on the origin of this facies other than that high-energy conditions prevailed during transportation. Likely depositional settings for conglomerate in glaciomarine environments are deltas, subaqueous outwash fans and beaches.

The facies assemblage making up the Urana Formation indicates that, in the Early Permian, the Murray Basin area was partly submerged beneath a shallow-marine sea, with glaciers encroaching on its edges at times, and with deltas prograding into it in places. Vertical facies changes in some wells indicate that the influence of glacial ice decreased with time.

Stratigraphic nomenclature and type section. These sediments were previously called Cape Jervis beds because of their similarity to that unit in the Troubridge Basin (Ludbrook, 1967b; O'Brien, 1981, Gorter, 1986a,b,c). However, their geographic separation from the Troubridge Basin equivalents prompted O'Brien (1986) to formally name them the Urana Formation. O'Brien (1986) defined the type section as the interval between 425 m and 1312 m in A.O.G. Jerilderie No.1 (lat. 35°15'S, long. 145°58'E; Fig. 34).

Stratigraphic relationships. The Urana Formation rests unconformably on Lower Palaeozoic basement or on Devonian sediments in some infrabasins. The Urana Formation is generally unconformably overlain by Tertiary sediments of the Murray Basin, but in the Ovens Graben (Oaklands Basin), it is overlain by Upper Permian coal measures; and in the Renmark, Wentworth, Tararra and Ivanhoe Troughs, as well as in the Paringa Embayment, it is unconformably overlain by Mesozoic sediments.

Correlative units. The Urana Formation correlates with other Late Palaeozoic glacial sequences in eastern Australia, such as those in central Victoria, the Cape Jervis beds of the Yorke and Fleurieu Peninsulas (Foster, 1974) and the Troubridge Basin (Ludbrook, 1967b) west of the Murray Basin, and the Merrimelia Formation in the Cooper Basin (O'Brien, 1986).

Aquifer characteristics. Little information is available on the groundwater resources of the Urana Formation. A few analyses are recorded in petroleum well completion reports, and geophysical logs show that the formation waters are brackish to saline, in some wells becoming more saline with depth. It is unlikely that these formation waters are in contact with groundwaters in the Murray Basin sediments above.

TABLE 6. COMPONENT UNITS – UPPER PERMIAN COORABIN COAL MEASURES

Formation	*Thickness (m)*	*Type Section*	*Interval (m)*	*Location*
Nowranie Creek Formation	0–7	DM Oaklands RDH 17	175.56–179.43	GR 162748, Urana 1:100,000
Coreen Creek Coal Member	0.5–1.5	DM Oaklands RDH 4	218.29–219.68	GR 052638, Berrigan 1:100,000
Loughmore Formation	7–18	DM Oaklands RDH 1	193.34–201.93	GR 096599, Buraja 1:100,000
Narrow Plains Formation	15–35	DM Oaklands RDH3	95.04–127.4	GR 215586, Buraja 1:100,000
Lane's Shaft Coal Member	3.5–19	DM Coorabin RDH 2	69.42–83.39	GR 266567, Buraja 1:100,000

Unit: Coorabin Coal Measures
Age: Late Permian
Map symbol: Pu
Component units: Lane's Shaft Coal Member, Narrow Plains Formation, Loughmore Formation, Coreen Creek Coal Member, Nowranie Creek Formation (Table 6).

Lithologies. The Narrow Plains Formation consists of off-white clayey coarse sand with conglomerate bands fining-up into grey and dark-brown carbonaceous clay and coal of the Lane's Shaft Coal Member. The Loughmore Formation is similar, with pebbly coarse sand at the base passing up into finer sand and silt into carbonaceous sand and silt and coal of the Coreen Creek Coal Member. The Nowranie Creek Formation consists of grey to pink clays (Yoo, 1982).

Distribution and thickness. The Coorabin Coal Measures are known only from beneath the southeastern corner of the Murray Basin. They form a thin sheet that reaches a maximum thickness of 70 m over the Ovens Graben and that extends across the Graben edges. The thicknesses of individual formations are listed in Table 6. Probable Coorabin Coal Measures have also been encountered in boreholes in the Numurkah Basin (e.g. Gates, 1986; Brinkley & others, 1988).

Structure. The Coorabin Coal Measures are flat-lying apart from some gentle folding parallel to the Ovens Graben axis (Yoo, 1982).

Palaeontology. The Coorabin Coal Measures contain palynomorphs and plant fragments such as *Vertabraria*.

Age evidence. The Narrow Plains Formation exhibits a Lower Stage 5 microflora, the Loughmore Formation an Upper Stage 5 microflora, and the Nowranie Creek Formation a *Protohaploxypinus reticulatus* assemblage (Morgan, 1977a). These assemblages indicate both a Late Permian age (Kemp & others, 1977) and the presence of unconformities between the individual formations (Morgan, 1977a).

Stratigraphic relationships. The Coorabin Coal Measures rest unconformably on Urana Formation and on basement where they overlap the Urana Formation. The Triassic Jerilderie Formation and Tertiary Murray Basin sediments overlie the Coorabin Coal Measures unconformably. Within the Coorabin Coal Measures, the units are separated by unconformities (Morgan, 1977,a,b).

Depositional environments. Morgan (1977a) interprets the Narrow Plains and Loughmore Formations as the products of meandering streams that deposited fining-up sequences, starting with coarse sand in the channel, passing up into clay, silt and coal on the floodplain.

Stratigraphic nomenclature. Coorabin Coal Measures comprise three formations: the Narrow Plains Formation which includes the Lane's Shaft Coal Member; the Loughmore Formation, including the Coreen Creek Coal Member; and the Nowranie Creek Formation (Table 6; Standing Committee on Coalfield Geology, 1976).

Type sections. The type sections of the components of the Coorabin Coal Measures are listed in Table 6.

Unit: Jerilderie Formation
Age: Mid-Triassic
Map symbol: TRm

Lithology. The Jerilderie Formation consists of white, pebbly cross-bedded sand, quartz pebble gravel, white to grey silt, and clay (Yoo, 1982).

Distribution and thickness. The Jerilderie Formation overlies the Coorabin Coal Measures in the northern half of the Ovens Graben, and extends an unknown distance beyond the graben edges. It is absent in the Oaklands area. The formation reaches a maximum thickness of 219 m in A.O.G. Jerilderie No.1 (Fig. 31), but elsewhere is between 70 and 200 m thick (Yoo, 1982).

Geometry. Yoo (1982) shows the Jerilderie Forma-

tion as a flat sheet that thickens over the Ovens Graben and is folded gently – with the Coorabin Coal Measures – about a fold axis parallel to the graben axis.

Stratigraphic relationships. The Jerilderie Formation unconformably overlies the Coorabin Coal Measures and older Palaeozoic basement where it overlaps the coal measures. The Tertiary Olney Formation of the Renmark Group rests unconformably on the Jerilderie Formation.

Palaeontology and age evidence. The only fossils yet recovered from the Jerilderie Formation are palynomorphs (McMinn, 1981; Morgan, 1977a). McMinn (1981) recognised the Mid-Triassic *Aratrisporites parvispinosus* microflora in the Jerilderie Formation.

Depositional environments. The Jerilderie Formation consists of fluvial channel and floodplain sediments.

Stratigraphic nomenclature and type section. In the past, the Jerilderie Formation was logged as Tertiary Renmark Group sediments because of their lithological similarity (Wright & Stuntz, 1963). The type section is in A.O.G. Jerilderie No.1 between 142.7 and 362.2 m (Standing Committee on Coalfield Geology, 1976). A cored reference section is located in DM Oaklands RDH 5 (Grid Reference 984737, Jerilderie 1:100 000 sheet).

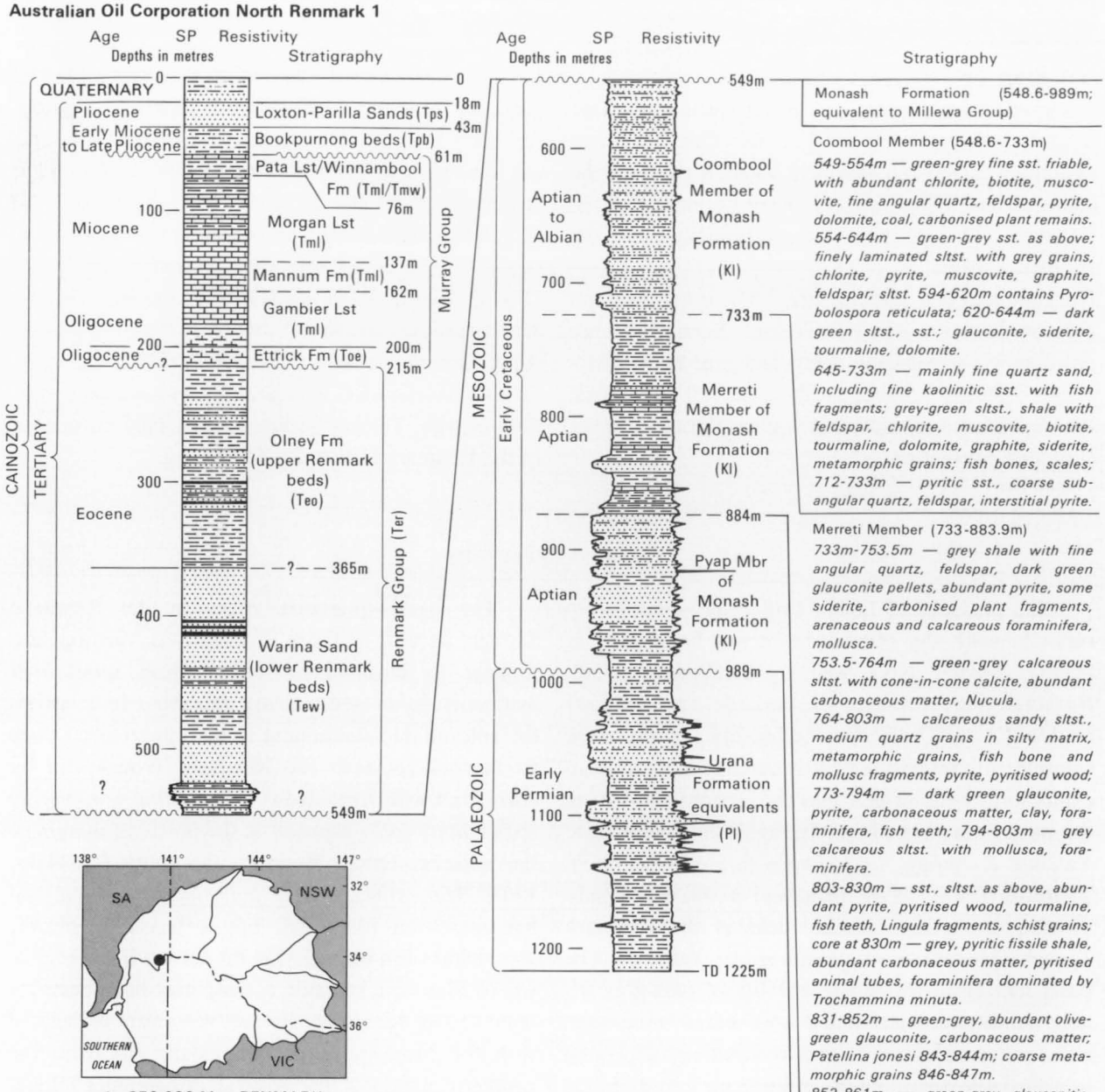
Aquifer characteristics. The Jerilderie Formation is directly overlain by, and possibly hydraulically continuous with, Tertiary sediments of Olney Formation of the Renmark Group aquifer system.

Lower Cretaceous

The presence of Lower Cretaceous sedimentary rocks beneath the Murray basin was first noted in A.O.G. Loxton No.1 well by Ludbrook (1956). Residual thin remnants of fluviatile and shallow-marine Lower Cretaceous sedimentary rocks were subsequently intersected by a number of petroleum exploration wells drilled into the troughs underlying the western and northern Murray Basin (Tables 7, 8; Yakunin & Sprigg, 1963; Evans & Hawkins, 1967). Thornton (1972, 1974) proposed a three-fold subdivision of Aptian–Albian rocks in the Renmark Trough (Monash Formation; Fig. 35; Table 7). The basal unit (Pyap Member) consists of pale-grey friable sandstone interbedded with minor mudstone, coal, and conglomerate, and was initially deposited in a fluviatile environment, grading up into a marine environment, as indicated by glauconite, arenaceous foraminifera and dinoflagellates. The succeeding Merreti Member consists of marine mudstone, siltstone, and minor sandstone, and is in turn overlain by Aptian–Albian interbedded green and grey chloritic siltstone, volcanilithic sandstone, and shale (Coombool Member) deposited in fluvio-lacustrine environments. In adjacent areas of northwest Victoria, Lawrence & Goldberry (1973) and Lawrence (1976d, 1988b) recognised a mainly fluviatile and lacustrine Lower Cretaceous succession (Millewa Group; Fig. 36; Table 9) with only minor marine influences, and adopted a two-fold subdivision comprising basal medium to coarse quartz sandstone (Taparoo Sandstone) overlain by interbedded siltstone, mudstone, and minor sandstone (Morkalla Formation).

The basal quartzose rocks in the Renmark Trough, as well as those in northwest Victoria, are thought to have been derived from quartz-rich metamorphic or sedimentary terranes. In contrast, the volcanilithic component in the uppermost Lower Cretaceous rocks in the Renmark Trough can be correlated with Cretaceous volcanilithic non-marine sedimentary rocks exposed at the northern margin of the adjacent Otway Basin to the south (Hawkins, 1967). The provenance of the volcanilithic material has not been identified, but a possible volcanic source has been identified in the Otway Basin region, where Mesozoic volcanic activity may have been related to late Mesozoic rift-drift volcanism associated with the breakup of Gondwanaland, to form the southern margin of the Australian continent (Boeuf & Doust, 1975; Falvey & Mutter, 1981). The marine sediments of the Renmark Trough area can be correlated with the partly marine Cretaceous Eromanga Basin succession of the Great Artesian Basin (Senior & others, 1978), rather than with the non-marine Otway Basin equivalents. Rogers (in press, a) has termed this southern extension of the Eromanga Basin, the 'Berri Embayment'. Essentially the Lower Cretaceous succession can be interpreted in terms of a transgressive–regressive cycle, related to a marine incursion of a shallow epeiric sea by invasion from the north, whereas the volcanilithic component may reflect fluvial sediment input, in part derived from the Otway Basin region.

Equivalent Lower Cretaceous sedimentary rocks of the Otway Group (Otway Basin; Wopfner & Douglas, 1971; Kenley, 1976b, 1988b) are exposed in



1 : 250 000 Map RENMARK

Latitude 34°07′00″S
Longitude 140°41′00″E
Drilled 1962/63
TD 1225m
GL 24m
KB 25m

Monash Formation (548.6-989m; equivalent to Millewa Group)

Coombool Member (548.6-733m)

549-554m — green-grey fine sst. friable, with abundant chlorite, biotite, muscovite, fine angular quartz, feldspar, pyrite, dolomite, coal, carbonised plant remains.
554-644m — green-grey sst. as above; finely laminated sltst. with grey grains, chlorite, pyrite, muscovite, graphite, feldspar; sltst. 594-620m contains Pyrobolospora reticulata; 620-644m — dark green sltst., sst.; glauconite, siderite, tourmaline, dolomite.
645-733m — mainly fine quartz sand, including fine kaolinitic sst. with fish fragments; grey-green sltst., shale with feldspar, chlorite, muscovite, biotite, tourmaline, dolomite, graphite, siderite, metamorphic grains; fish bones, scales; 712-733m — pyritic sst., coarse sub-angular quartz, feldspar, interstitial pyrite.

Merreti Member (733-883.9m)

733m-753.5m — grey shale with fine angular quartz, feldspar, dark green glauconite pellets, abundant pyrite, some siderite, carbonised plant fragments, arenaceous and calcareous foraminifera, mollusca.
753.5-764m — green-grey calcareous sltst. with cone-in-cone calcite, abundant carbonaceous matter, Nucula.
764-803m — calcareous sandy sltst., medium quartz grains in silty matrix, metamorphic grains, fish bone and mollusc fragments, pyrite, pyritised wood; 773-794m — dark green glauconite, pyrite, carbonaceous matter, clay, foraminifera, fish teeth; 794-803m — grey calcareous sltst. with mollusca, foraminifera.
803-830m — sst., sltst. as above, abundant pyrite, pyritised wood, tourmaline, fish teeth, Lingula fragments, schist grains; core at 830m — grey, pyritic fissile shale, abundant carbonaceous matter, pyritised animal tubes, foraminifera dominated by Trochammina minuta.
831-852m — green-grey, abundant olive-green glauconite, carbonaceous matter; Patellina jonesi 843-844m; coarse metamorphic grains 846-847m.
852-861m — green-grey glauconitic, kaolinitic sst. with wood fragments, blue-green clay matrix.
861-866m — brownish pyritic sst., feldspar, carbonaceous silty matrix.
866-883.9m — grey carbonaceous mudst. with fine muscovite abundant carbonised plant material.

Pyap Member (883.9-989m)

883.9-898m — grey carbonaceous mudst. over coarse quartz grit; angular to sub-angular clear, milky, grey quartz, feldspar; feldspathic matrix; pyrite.
902-905m — soft grey mudst., scattered coarse sub-angular quartz grains, fine muscovite, carbonaceous matter; light grey sandy sltst., v. fine sst., fine to medium quartz, abundant muscovite, clay, carbonised plant fragments, scales; kaolinitic silty sst.
905-918m — mudst. as above, gritty quartz sst.
918-951m — medium to coarse feldspathic sst., coal fragments and bands.
951-977m — gritty sst. with quartz, coarse metamophic grains, feldspathic matrix; 968-977m contains coal, coarse grit.
977-989m — sst. as above.

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Fig. 35. Lithology log of Australian Oil Corporation North Renmark No. 1 — including type section of Lower Cretaceous Monash Formation (based on Grasso, 1963; Thornton, 1972).

TABLE 7. PYAP, MERRETI AND COOMBOOL MEMBERS OF THE LOWER CRETACEOUS MONASH FORMATION

Unit: Pyap Member of Monash Formation

Age: Early Cretaceous Aptian (114–119 Ma)

Map symbol: included in Kl

Lithology. Mainly medium to very coarse, pebbly, friable sandstone; minor interbedded claystone, fine-grained to silty sandstone; minor coal towards base in A.O.C. North Renmark No.1 (Grasso, 1963). Mainly, well-sorted, angular to rounded, clear to white/grey quartz; minor feldspar, coarse metamorphic grains; accessory carbonaceous material, muscovite, chlorite, minor pyrite; kaolinitic clay matrix; glauconite tentatively identified in claystone interbeds (Thornton, 1972). Bedding generally sub-horizontal; cored material from Beach Monash No.1 cross-bedded.

Distribution and thickness. Restricted to deeper parts Renmark Trough and Paringa Embayment; possibly present in deeper parts of adjacent Tararra Trough and Canegrass Lobe. Exploration wells indicate thins toward trough margins; absent from Cretaceous sections preserved over up-faulted but concealed basement blocks flanking Renmark Trough and Paringa Embayment. Thickest section – 109 m in Beach Berri North No.1 (805–914 m; Fig. 38; Laws & Heisler, 1967). Identified by Thornton (1974) in other petroleum exploration wells (Table 8).

Palaeontology and age evidence. Abundant arenaceous foraminifera in upper part (Ludbrook, 1963c); minor coal bands in lower part. Foraminifera from top dated as Aptian (Ludbrook, 1963c); pollen, spores dated uppermost Jurassic to Aptian (Harris, 1963). Subsequent palynological age determinations from A.A.O. Nadda No.1, Sunset No.1, Morkalla No.1 (Paten & Price, 1970) indicate Aptian age; correlated with Cyclosporites hughesii subzone of Dettmann & Playford (1969) – equivalent to Cyclosporites hughesii zone (114–119 Ma) of Helby & others (1987).

Environment of deposition. Presence of abundant arenaceous foraminifera, possible presence of glauconite, indicate upper section of Pyap Member deposited under marine conditions. Laws & Heisler (1967) suggested sandstone in Beach Berri North No.1 deposited in marginal-marine barrier island environment, during Early Cretaceous marine transgression. In contrast, Derrington & Anderson (1970) suggested sandstone in A.A.O. Nadda No.1, Sunset No.1, Morkalla No.1, deposited in fluvial environments within palaeo-valleys of Paringa Embayment. Thornton (1972) suggested basal sequence fluviatile, but grades up-sequence into marine-dominated upper section.

Stratigraphic nomenclature and type section. Named after Pyap Lagoon on Murray River 18 km WNW of Loxton (RENMARK); Thornton (1972) nominated interval 883.9–989.1 m, in A.O.C. North Renmark No.1, as type section (Fig. 35).

Synonyms. Pyap Member of Monash Formation in S.A. appears to correlate directly with Taparoo Sandstone of Millewa Group in adjacent areas of NW Victoria (Fig. 37).

Stratigraphic relationships. Pyap Member of Monash Formation disconformable over Lower Permian sediments in Paringa Embayment, Renmark and Tararra Troughs. Towards margins of Paringa Embayment unconformably onlaps Palaeozoic basement rocks. Conformable under, and transitional with, overlying Merreti Member.

Aquifer/reservoir characteristics. Sandstone characterised by good porosity, permeability.

Unit: Merreti Member of Monash Formation

Age: Early Cretaceous Aptian (110–116 Ma)

Map symbol: included in Kl

Lithology. Mainly grey shale, mudstone, interbedded with grey, green siltstone, and fine to fine-grained, light grey to green-grey sandstone. Shale has flattened clay balls, black clay pellets, dark-green glauconitic pellets, abundant pyrite, carbonaceous plant fragments, minor lithic pebbles, cobbles. Contains fine-grained angular quartz, in addition to feldspar, minor mica. Interbedded sandstone has subangular quartz, glauconite, mica, kaolinised specks, intraclasts of mudstone. Matrix in sandstone, mainly argillaceous clay, local calcareous cement; minor micritic limestone also recorded (Thornton, 1974). Slump structures in mudstone, contorted bedding, vertical worm burrows reported in Beach Berri North No.1 (Laws & Heisler, 1967); current bedding noted in sandstone cores.

Distribution and thickness. Encountered in most petroleum exploration wells in Renmark Trough area. Unlike underlying Pyap Member, not confined to deeper parts of troughs, but extends over adjacent concealed basement areas. Thickest sections – 151 m in A.O.C. North Renmark No.1 (733–884 m; Fig. 35; Grasso, 1963), 120 m in Claremont Kopi Plain No.1 (337–497 m; Fig. 29; Gorter, 1986c), 113 m in Beach Berri North No.1 (692–805 m; Fig. 38; Laws & Heisler, 1967); thick sequences also encountered in several other petroleum exploration wells (Thornton, 1974; Table 8).

Palaeontology and age evidence. Towards base in A.O.C. North Renmark No.1, abundant arenaceous, calcareous foraminifera in addition to mollusca, fish fragments, Lingula fragments, pyritised wood (Ludbrook, 1963c). Foraminiferal assemblages indicate Aptian age (Ludbrook, 1963c). Foraminiferal and palynological age determinations from A.A.O. Nadda No.1, Sunset No.1, Morkalla No.1 (Paten & Price, 1970) indicate Aptian age, spanning upper Cyclosporites hughesii subzone and Crybelosporites striatus subzone of Dettmann & Playford (1969) – equivalent to Cyclosporites hughesii and Crybelosporites striatus zones (110–116 Ma) of Helby & others (1987).

Environment of deposition. Presence of glauconite, arenaceous foraminifera, dinoflagellates, vertical worm burrows indicate marine environment; Thornton (1972) suggested shale and siltstone, marginal-marine quiet-water deposits.

Stratigraphic nomenclature and type section. Named after Lake Merreti in floodplain of Murray River 20 km north of Renmark (northeast RENMARK); Thornton (1972) nominated interval 733–883.9 m, in A.O.C. North Renmark No.1, as type section (Fig. 35).

Synonyms. Equivalent to lower part of Morkalla Formation of Millewa Group in adjacent areas of NW Victoria (Fig. 37).

Stratigraphic relationships. In places, Merreti Member of Monash Formation unconformably onlaps Palaeozoic basement rocks, but mainly conformable over Pyap Member, conformable under Coombool Member.

Aquifer/reservoir characteristics. Sandstone intervals in Merreti Member generally characterised by poor porosity, permeability.

Unit: Coombool Member of Monash Formation

Age: Early Cretaceous, Aptian to Albian (102.5–110 Ma)

Map symbol: included in Kl

Lithology. Variable proportions of interbedded grey to grey-green sandstone, medium grey siltstone, light to dark-grey clay. Sandstone mainly well sorted, sub-angular, very fine to fine-grained quartz; minor feldspar, chert, muscovite, dolomite, chlorite, graphite; matrix locally calcareous. Siltstone sandy, quartzose to carbonaceous, with rare detrital coal fragments. Clay soft, sticky, silty, micaceous, lignitic, pyritic. Minor conglomerate interbeds also recorded (Thornton, 1972). Horizontal bedding observed in cores.

Distribution and thickness. Identified over most of Renmark Trough and adjacent areas. Thickest section – 184.4 m in A.O.C. North Renmark No.1 (548.6–733 m; Fig. 35).

Palaeontology and age evidence. Abundant plant megaspores Arcellites reticulata, Arcellites hexapartita; fish remains (Ludbrook, 1963c). Palynological age determinations from A.O.C. North Renmark No.1 (Ludbrook, 1963c; Evans & Hawkins, 1967) indicate Aptian to Albian age, based on correlation with Coptospora paradoxa zone of Dettmann & Playford (1969) – and similarly named zone (102.5–110 Ma) of Helby & others (1987).

Environment of deposition. Based mainly on abundant presence of plant material, and apparent absence of foraminifera/dinoflagellates, thought to be freshwater deposits.

Stratigraphic nomenclature and type section. Named after Coombool Swamp in Murray River floodplain, 35 km NNE of Renmark (southeast CHOWILLA). Thornton (1972) nominated interval 548.6–733 m, in A.O.C. North Renmark No.1, as type section (Fig. 35).

Synonyms. Equivalent to upper part of Morkalla Formation in adjacent areas of NW Victoria (Fig. 37).

Stratigraphic relationships. Coombool Member of Monash Formation conformable over Merreti Member. Upper surface disconformable under Paleocene–Eocene sediments of overlying Tertiary Murray Basin sequence. Presence of very thin sediments of uppermost Coombool Member, in some wells, indicates unit truncated by erosion prior to deposition of overlying Tertiary.

Aquifer/reservoir characteristics. Lithic sandstone characterised by poor porosity, permeability.

TABLE 8. PETROLEUM EXPLORATION WELLS WHICH ENCOUNTERED LOWER CRETACEOUS ROCKS

	Millewa Group									
	Monash Fmtn		*Pyap Mmbr*		*Merreti Mmbr*		*Coombool Mmbr*		*Fig*	*Reference*
Well	*Depth*	*Thickn.*	*Depth*	*Thickn.*	*Depth*	*Thickn.*	*Depth*	*Thickn.*		
	(metres)									
Claremont Avery 1	304	100	367	37	304	63	–	–	29	Gorter (1986a)
Beach Berri North 1	524	390	805	109	692	113	524	168	38	Laws & Heisler 1967)
Beach Berri South 1	498	151	–	–	602	47	498	104	38	Gausden & Watts (1966))
Intern. Mining Cooltong 1	507	426	839	94	675	164	507	168	–	Archer (1988)
Ironstone Tank 1	304	108	370	42	304	66	–	–	29	Gorter (1986b)
Claremont Kopi Plain 1	377	150	497	30	377	120	–	–	29	Gorter (1986c)
A.O.G. Lake Victoria 1	543	164	–	–	660	47	543	117	39	Grasso (1964)
Beach Loxton 2	408	134	512	30	430	82	408	22	40	Laws (1963)
Beach Monash 1	536	357	811	82	701	110	536	165	38	Walter (1965)
A.A.O. Morkalla 1	581	161	–	–	674	68	581	93	39	Derrington & Anderson (1970)
A.A.O. Nadda 1	449	180	556	73	472	84	449	23	40	Derrington & Anderson (1970)
A.A.O. Sunset 1	641	286	872	55	792	80	641	151	36	Derrington & Anderson (1970)
A.O.C. North Renmark 1	549	440	884	105	733	151	549	184	35	Grasso (1963)
A.O.G. Intern. Mining Overland Corner 1	270	328	459	139	344	115	270	74	–	Furr (1984)
Tararra 1	492	91	558	25	492	66	–	–	28	Boyd & Heisler (1967)
A.O.G. Wentworth 1	388	101	–	–	435	54	388	47	39	Rose (1962a)

Other wells which have encountered undifferentiated Lower Cretaceous

Well	*Depth*	*Thickness (metres)*		*Reference*
North Star Conoble 1	119	64	–	North Star (1962)
Esso Ennisvale 1	427	129	–	Sniffen (1985)
North Star Ivanhoe 1	164	40	30	Brundall (1964)
N.S.W. Oil & Gas Nambucurra 1	?216	28	–	Sniffen (1985)
Esso Popiltah 1	355	170	–	Archbold (1984) & McMaugh (1984d)

the Casterton region of western Victoria. Small outcrops of these Otway Basin rocks are exposed along the course of the Kadnook Creek (tributary of the Glenelg River on HAMILTON), beneath the Loxton–Parilla Sands of the southern Murray Basin, and have also been encountered in boreholes elsewhere on HAMILTON (Lawrence, 1975, 1976d, 1988b). These sediments are generally only a few metres thick, and consist of lateritised claystone, mudstone, siltstone, sandstone, and gravel, with plant material indicating correlation with older components of the Otway Group (Douglas, 1969; Lawrence, 1975).

Beneath northern areas in New South Wales, Albian marine and Aptian–Neocomian non-marine carbonaceous rocks have been encountered in the Ivanhoe Trough area (Fig. 23; Byrnes, 1980; Yoo, 1981b). North Star Ivanhoe No.1 well (Fig. 30) encountered 39.6 m of Lower Cretaceous sediments (164 to 203.6 m). These consist of fine-grained, loosely cemented, subangular, porous quartz sandstone, and fine to medium-grained, rounded to subangular, porous sandstone with light and dark-grey clay stringers (Brundall, 1964). The sequence

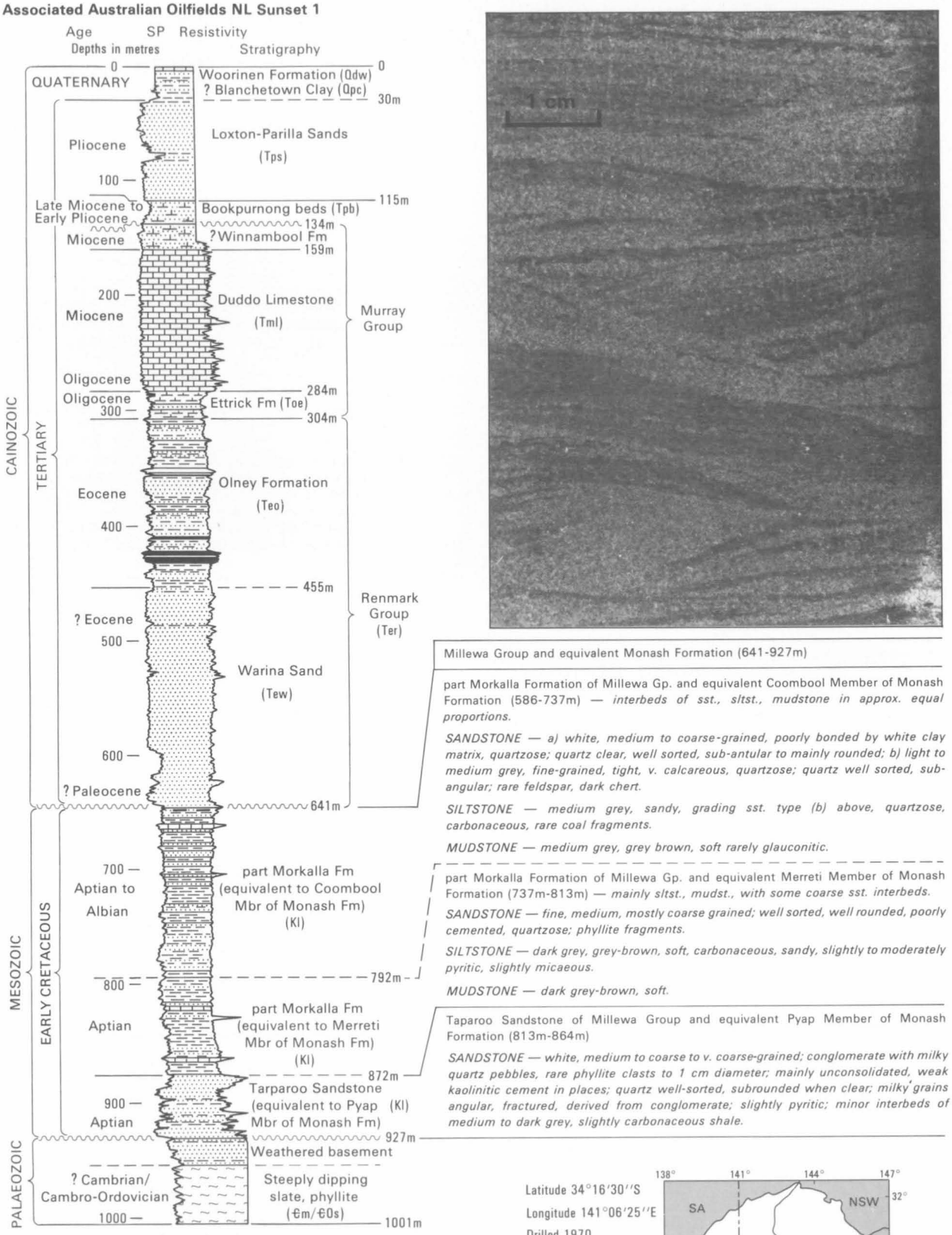

Fig. 36. Lithology log of Associated Australian Oilfields Sunset No. 1 — including type section of Lower Cretaceous Taparoo Sandstone and Morkalla Formation of Millewa Group (based on Derrington & Anderson, 1970; Thornton, 1974; Lawrence, 1975, 1976d; N.B. see Fig. 37 for correlation between South Australian and Victorian Lower Cretaceous stratigraphic schemes.

TABLE 9. TAPAROO SANDSTONE AND MORKALLA FORMATION OF THE LOWER CRETACEOUS MILLEWA GROUP

Unit: Taparoo Sandstone of Millewa Group

Age: Early Cretaceous Aptian (114 – 118.5 Ma)

Map symbol: included in Kl

Lithology. White, medium to coarse-grained, quartzose sandstone, locally pyritic, carbonaceous (Fig. 36).
Distribution and thickness. Identified in boreholes in NW Victoria. Thickest sequence – 55 m, in A.A.O. Sunset No.1 (872 – 927 m; Fig. 36; Derrington & Anderson, 1970).
Palaeontology and age evidence. Plant debris. Age determinations (Paten & Price, 1970) indicate correlation with Aptian Cyclosporites hughesii subzone of Dictyotosporites speciosus zone of Dettmann & Playford (1969) – equivalent to Cyclosporites hughesii zone (114 – 118.5 Ma) of Helby & others (1987). In Vic.D.M. Olney No.1, cuticular remains of conifers (Lawrence, 1966).
Environment of deposition. Fluvial and lacustrine deposits (Lawrence, 1975).
Stratigraphic nomenclature and type section. Named after Parish of Taparoo; Millewa Group named after Parish of Millewa – both parishes in MILDURA. Lawrence (1972, 1975) nominated 55 m section, in A.A.O. Sunset No.1 (872 – 927 m), as type section (Fig. 36; Derrington & Anderson, 1970; Lawrence & Goldberry, 1973).
Synonyms. Comparisons between stratigraphic units of NW Victoria and adjacent areas of S.A. suggest Taparoo Sandstone correlates with (and synonymous with) Pyap Member of Monash Formation (Fig. 37).
Stratigraphic relationships. Basal unit of Millewa Group. Unconformable over Palaeozoic basement rocks. Disconformable over Lower Permian sedimentary rocks in places. Conformable under Morkalla Formation of Millewa Group

Unit: Morkalla Formation of Millewa Group

Age: Early Cretaceous, Aptian – Albian (102.5 – 114 Ma)

Map symbol: included in Kl

Lithology. Interbedded siltstone, mudstone, minor sandstone.
Distribution and thickness. Identified in boreholes in NW Victoria. Thickest sequence – 231 m in A.A.O. Sunset No.1 (641 – 872 m; Fig. 36; Derrington & Anderson, 1970).
Palaeontology and age evidence. Carbonaceous plant debris; foraminifera in shale intervals in Vic.D.M. Olney No.1 (Lawrence, 1975). Spans Cyclosporites striatus subzone of upper Dictyotosporites speciosus zone and Coptospora paradoxa zone of Dettmann & Playford (1969) of Aptian – Albian, Early Cretaceous age (Lawrence, 1975) – equivalent to similarly named zones (102.5 – 114 Ma) of Helby & others (1987).
Environment of deposition. Lawrence (1975) suggested mainly fluvial and lacustrine deposits, with minor marine intercalations (see Table 7).
Stratigraphic nomenclature and type section. Named after township of Morkalla (MILDURA). Lawrence (1972, 1975) nominated 231 m section, in A.A.O. Sunset No.1 (641 – 872 m), as type section (Fig. 36; Derrington & Anderson, 1970; Lawrence & Goldberry, 1973).
Synonyms. Stratigraphically equivalent to Merreti and Coombool Members of Monash Formation in adjacent Renmark Trough in S.A. (Fig. 37).
Stratigraphic relationships. Upper unit of Millewa Group. Conformable over Taparoo Sandstone. Unconformable over Palaeozoic basement elements. Disconformable under Cainozoic sediments of Renmark Group.

contains plant remains and a marine dinoflagellate fauna of probable Aptian to early Albian age (Terpstra & others, 1964; Terpstra, 1967).

In North Star Conoble No.1, 64 m of partly marine Lower Cretaceous sediments of possible Aptian or older age have been identified (119 m to 183 m) by the presence of spore assemblages and dinoflagellates (Hodgson, *in* Evans & Hawkins, 1967). The Conoble No.1 section consists of dark grey to blue-grey, slightly sandy and carbonaceous clay, with fine to coarse-grained argillaceous sand with traces of pyrite (Sniffen, 1985).

A 56.5 m thick sequence of Lower Cretaceous sediments was encountered in NSW D.M. Umalee No.1 coal exploration bore (Yoo, 1981b). The uppermost 14 m of grey, micaceous, cohesive clay are of marine origin. The underlying sequence is thought to be entirely non-marine. At the top, it consists of 43 m of light-grey, fine to coarse sand, sandstone, and carbonaceous sandstone with abundant leaves and twigs, and thin coal bands. These overlie a basal 11 m thick section of pebble conglomerate. At a depth of 101.3 m, the marine interval contains a dinoflagellate assemblage of Early Aptian age, whereas the underlying non-marine sequence has palynological assemblages indicating a Neocomian age (McMinn, 1981).

The extent of remnant Lower Cretaceous sedimentary rocks beneath the northern Murray Basin is not well established (Fig. 23). Some non-marine sequences, such as that encountered in NSW D.M. Umalee No.1 bore, are lithologically similar to overlying sediments of the Tertiary Renmark Group, and consequently may not have been identified within some water bores. Recent joint BMR/DWR (NSW) drilling, for example, has identified the presence of Lower Cretaceous sediments on ANABRANCH (Macphail, 1987) and northwest POONCARIE (Truswell, 1987). Martin (1984a,b) has also identified microfloral assemblages of Early Cretaceous age in a number of scattered water bores drilled beneath the northern Murray Basin by the N.S.W. Department of Water Resources. Lower Cretaceous rocks have not as yet been identified in nearby water bores, reflecting their patchy distribution. The extent of Lower Cretaceous rocks beneath the Murray Basin is therefore uncertain, particularly beneath northern and northwestern areas, and they may be lithologically more variable and more widely distributed than is currently known. Stratigraphic units have therefore been defined only within the better-known sequence encountered by boreholes in the Renmark Trough region beneath the central-western part of the Murray Basin.

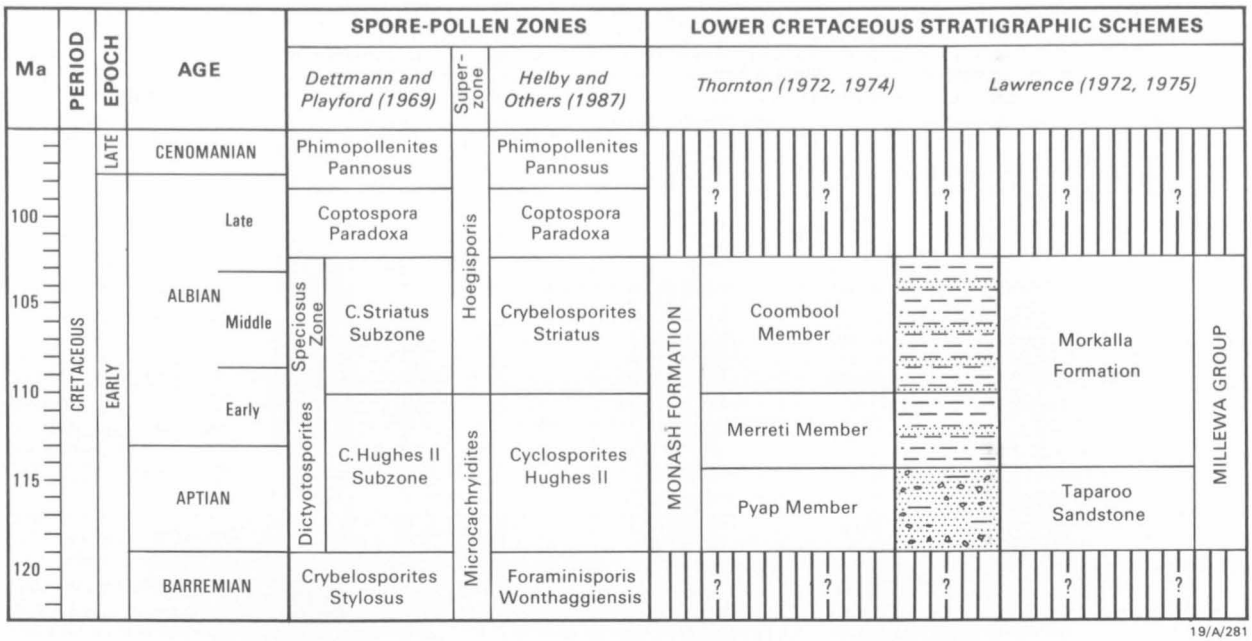

Fig. 37. Correlation between Lower Cretaceous stratigraphic schemes of Thornton (1972, 1974) in South Australia and Lawrence (1972, 1976d) in Victoria.

Lower Cretaceous units

The following descriptions of the Monash Formation and its members in the Renmark Trough in South Australia are largely based on the original definitions of Thornton (1972) and subsequent elaborations in Thornton (1974). Descriptions of the Lower Cretaceous Millewa Group and its formations in adjacent areas of northwest Victoria (Paringa Embayment) are taken from Lawrence (1972, 1975, 1976d, 1988b) and Lawrence & Goldberry (1973). Correlations between the two stratigraphic schemes (Fig. 37) suggest that the basal Taparoo Sandstone of the Millewa Group in northwest Victoria is equivalent to the Pyap Member of the Monash Formation in the Renmark Trough. Similarly, the Morkalla Formation of the Millewa Group can be correlated with the Merreti and Coombool Members of the Monash Formation (Fig. 37). The Lower Cretaceous units are entirely concealed beneath the Murray Basin and are poorly known outside the Renmark Trough. Consequently, although Thornton's stratigraphic scheme can be applied throughout the Renmark Trough and adjacent areas, the regional applicability of the scheme has not yet been established. It is herein suggested that the nomenclature of Thornton (1974) – 'Monash Formation' – be adopted where feasible, but it is also suggested that the 'Millewa Group' of Lawrence (1975) be retained on an informal basis until component formations can be more fully defined.

Unit: Monash Formation
Age: Early Cretaceous (Aptian to Albian)
Map symbol: Kl
Members: Pyap Member, Merreti Member, Coombool Member (Table 7)
Equivalent unit: Millewa Group (Table 9)

Lithology. The Monash Formation consists of interbedded sandstone, siltstone and shale. Quartz sandstone predominates at the base of deeper sections (Pyap Member); these grade upwards to a predominantly shale sequence (Merreti Member), overlain by interbedded lithic sandstone, siltstone, and shale (Coombool Member – see Table 7 for descriptions of component members). Petrographic descriptions of macroscopic samples and thin-sections from a number of petroleum exploration wells are given in Evans & Hawkins (1967).

Distribution and thickness. The formation has been identified within several petroleum exploration wells drilled in and adjacent to the Renmark Trough. Similar Cretaceous sediments have been encountered in the Paringa Embayment, and in the Wentworth, Tararra, and Menindee Troughs of western New South Wales. The formation is generally less than 100 m thick, but thicker sequences have been encountered in places (Table 8). Interpretations of

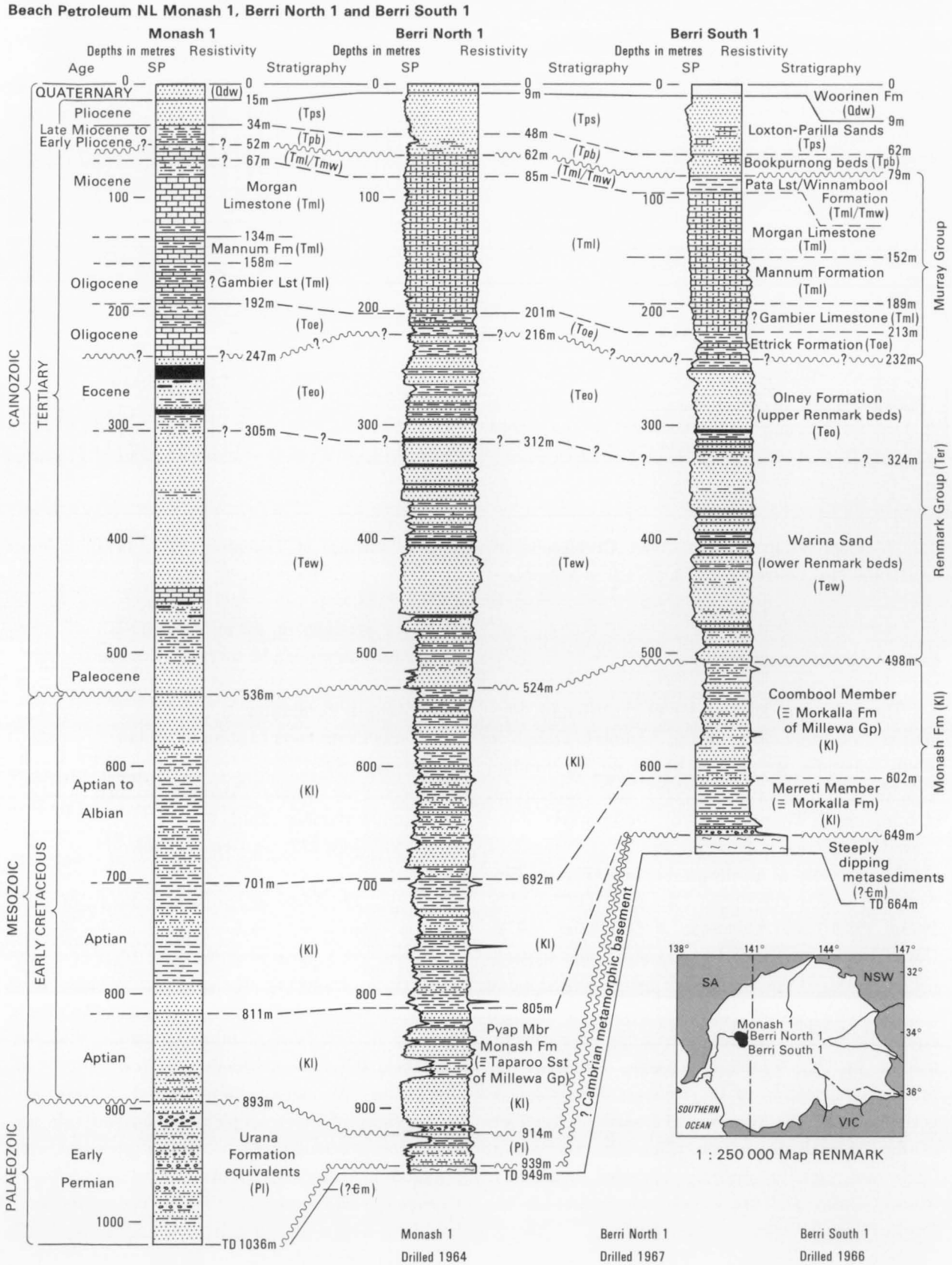

Fig. 38. Lithology logs of Beach Petroleum Monash No. 1, Berri North No. 1, Berri South No. 1 (based on Walter, 1965; Gausden & Watts, 1966; Laws & Heisler, 1967; Thornton, 1974).

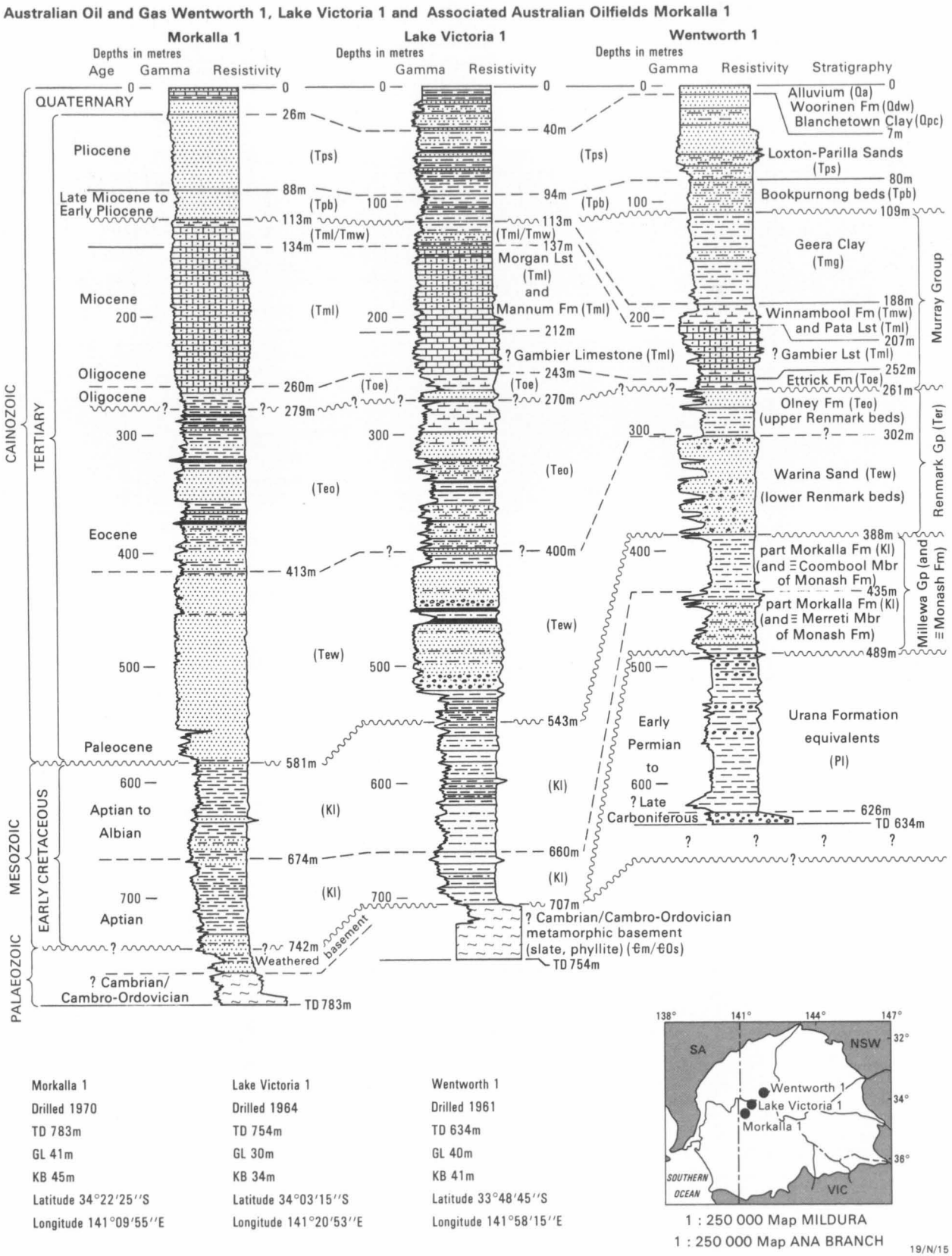

Fig. 39. Lithology logs of Australian Oil & Gas Wentworth No. 1, Lake Victoria No. 1, and Associated Australian Oilfields Morkalla No. 1 (based on Rose, 1962a; Grasso, 1964; Derrington & Anderson, 1970).

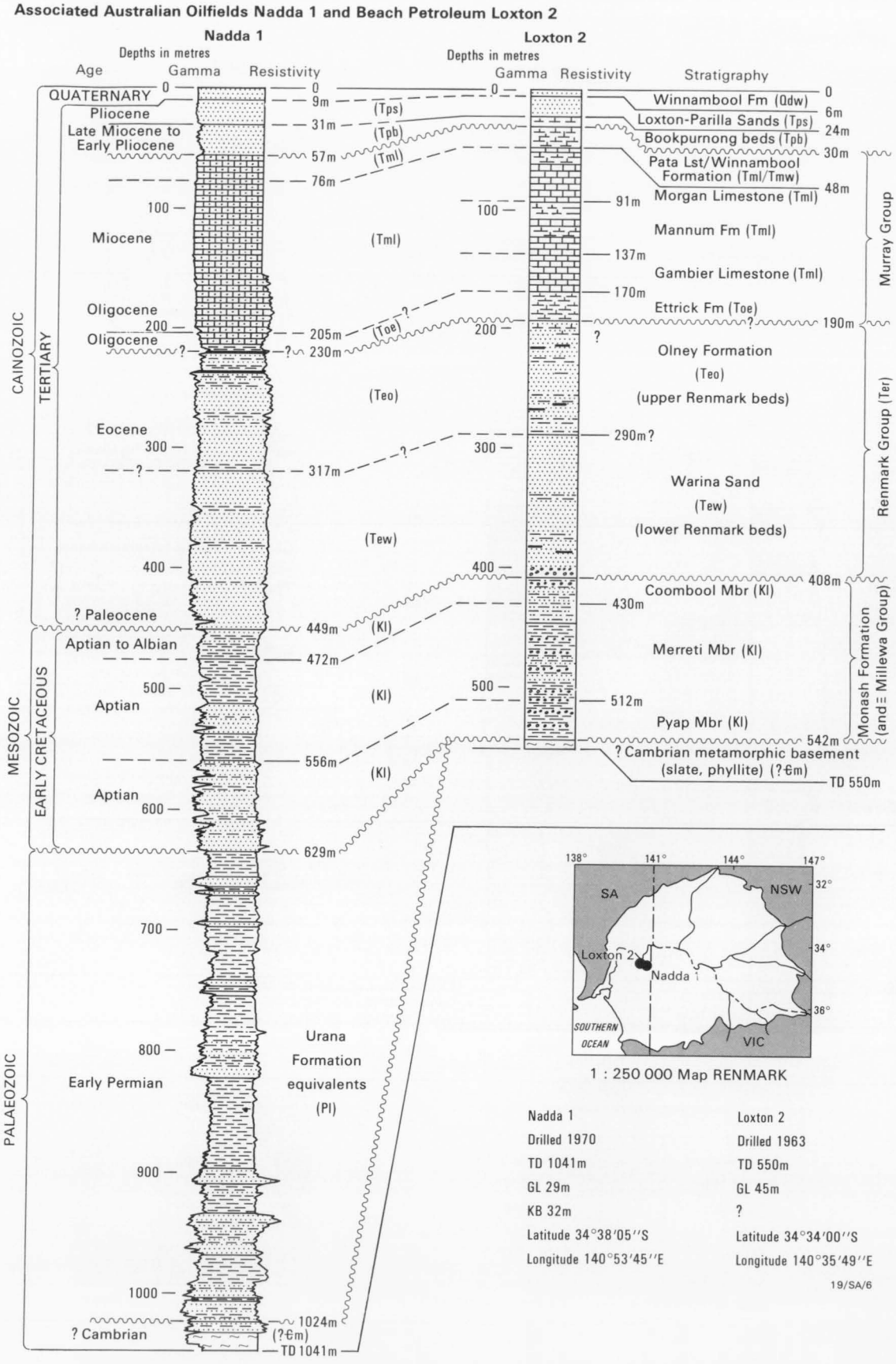

Fig. 40. Lithology logs of Associated Australian Oilfields Nadda No. 1, and Beach Petroleum Loxton No. 2 (based on Laws, 1963; Derrington & Anderson, 1970; Thornton, 1974).

seismic data suggest that the unit is up to 600 m thick in southern areas of the Renmark Trough (Thornton, 1972).

Palaeontology and age evidence. An Early Cretaceous age was first determined by Ludbrook (1956, 1958a, 1961a) following examination of samples from A.O.G. Loxton No.1 well. Additional age determinations indicating a general Cretaceous or Early Cretaceous Aptian to Albian age range were obtained from foraminiferal and/or palynological assemblages from A.O.G. Loxton No.1 (Cookson & Dettmann, 1958; Dettmann, 1963), A.O.C. North Renmark No.1 (Ludbrook, 1963c; Evans & Hawkins, 1967), A.O.G. Lake Victoria No.1 (Ludbrook, 1964), Beach Monash No.1 (Harris, 1965), Beach Berri North No.1 (Evans, 1967a), BMR/DWR (NSW) Manilla No.1 (Macphail, 1987), and BMR/DWR (NSW) Mitfords Corner No.1 (Truswell, 1987). A regional review of the palynostratigraphy of the Lower Cretaceous is given in Morgan (1980).

Interpretation of environment of deposition. It has been suggested that deposition of the Monash Formation can be correlated with a transgressive–regressive marine incursion by an epeiric sea from the Great Artesian Basin (Eromanga Basin) to the north (Evans & Hawkins, 1967). The basal Pyap Member is thought to have been deposited in fluvial to marine environments during the initial marine transgression, the intermediate Merreti Member during a subsequent period of marine deposition, and the uppermost Coombool Member in freshwater environments following the final marine regression. Equivalent sediment to the northeast [Aptian–Early Albian in BMR/DWR (NSW) Manilla No.1, Macphail, 1987; and Neocomian–Albian in BMR/DWR (NSW) Mitfords Corner No.1, Truswell, 1987] are thought to be entirely non-marine, and include charcoal conglomerates, with clasts formed by burning of conifer forests in the Early Cretaceous (Macphail & Truswell, 1988, 1989).

Stratigraphic nomenclature and type section. The formation was named after the township of Monash 8 km northeast of Barmera in northern RENMARK, and Thornton (1972) nominated the interval between 548.6 and 989.1 m in A.O.C. North Renmark No.1 as the type section (Fig. 35).

Synonyms. The unit is equivalent to the Millewa Group (Table 9) of Lawrence (1972, 1975, 1976d, 1988b) and Lawrence & Goldberry (1973).

Stratigraphic relationships. The Monash Formation mainly disconformably overlies Lower Permian sedimentary rocks within the Renmark Trough, and unconformably onlaps older Palaeozoic basement rocks beyond the margins of the trough. Seismic sections indicate that an angular unconformity separates the Lower Cretaceous from the underlying Lower Permian sediments adjacent to the Hamley Fault (Associated Australian Oilfields, 1968). The unit is disconformably overlain by Tertiary sedimentary rocks of the Renmark Group (Ter).

Aquifer/reservoir characteristics. Sandstone within the basal Pyap Member is characterised by excellent porosity values of up to 38%, and high permeabilities of up to 2000 millidarcies.

Data sources. Detailed lithological descriptions of the formation are provided in petroleum well completion reports from bores drilled in the Renmark Trough and adjacent areas (referenced Table 7). Petrographic descriptions are given in Evans & Hawkins (1967) and general descriptions of the regional character of the formation in Thornton (1972, 1974), and Rogers (in press, a).

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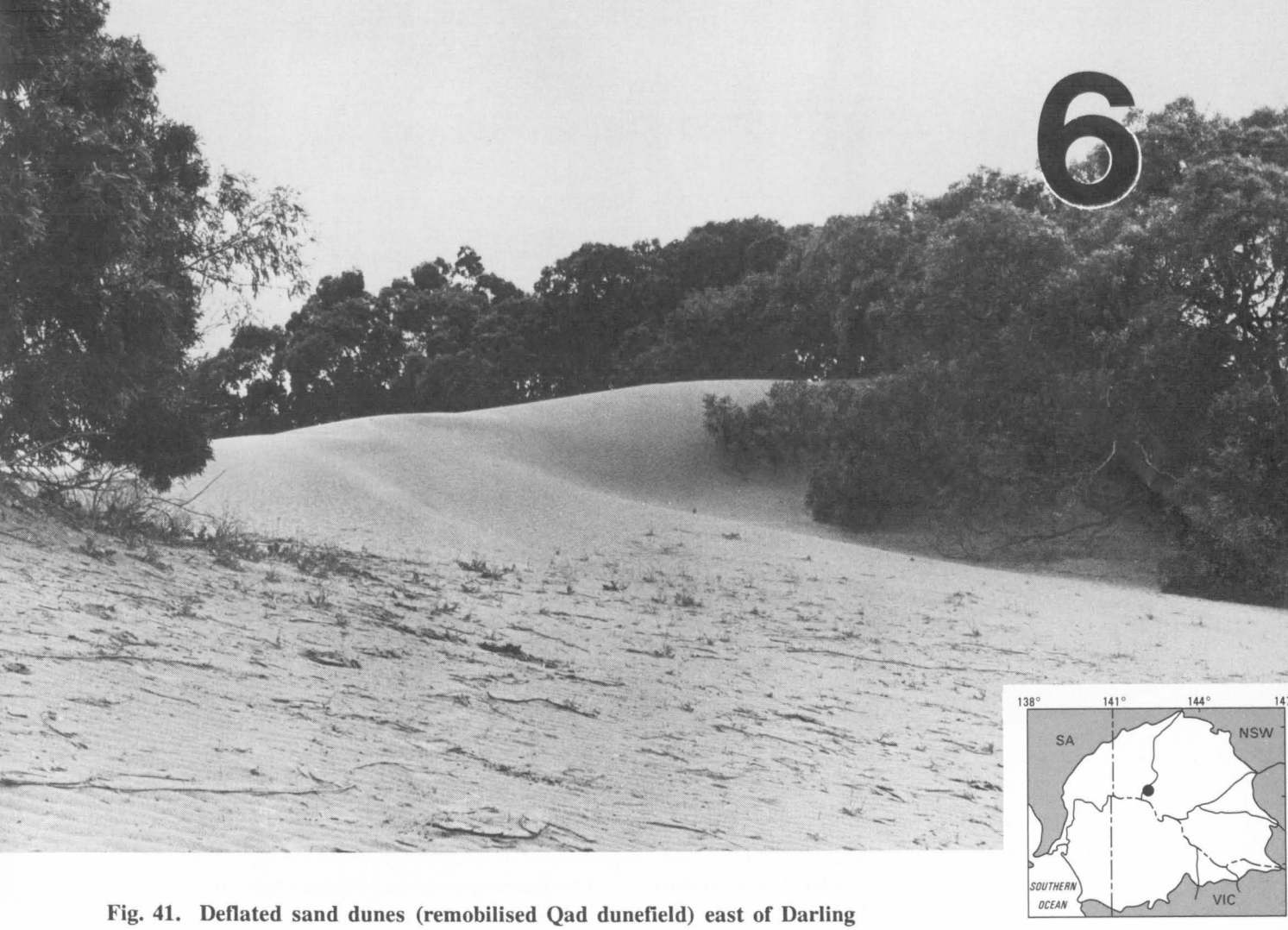


Fig. 41. Deflated sand dunes (remobilised Qad dunefield) east of Darling River (southern ANABRANCH).

CAINOZOIC STRATIGRAPHY – A SYNOPSIS

Cainozoic stratigraphic schemes have been established in each of the three States, but correlation difficulties between these schemes, and a lack of uniformity of stratigraphic nomenclature has necessitated development of a basin-wide stratigraphic framework. This study has allowed us to clarify a number of stratigraphic problems, but we have not attempted to redefine existing detailed nomenclature, and the basic objective has been to allow lithostratigraphic units to be examined as single entities within a basin-wide stratigraphic framework. The more significant correlations, along with recommendations for future uniformity of stratigraphic nomenclature, are discussed in the following detailed descriptions of units. The Tertiary stratigraphic schemes previously devised in each of the three States are shown in Figures 42, 43, and 44, and the basin-wide scheme, as used in this Bulletin, is illustrated in Figure 45. The basin-wide scheme reflects the results of investigations previously undertaken by colleagues in State organisations, and our descriptions of stratigraphic units have been compiled mainly from the numerous observations recorded in both the published and unpublished report series of the various State surveys. The large number of local and regional stratigraphic names, which have previously been applied in the Murray Basin, are listed in Appendix 2, which also shows the relationship between these names and the basin-wide stratigraphic scheme adopted in this Bulletin.

The Tertiary stratigraphy of the Murray Basin in South Australia was initially developed in the course of hydrogeological investigations by Ludbrook (1957, 1958a, 1961a, 1963a, 1969a, 1973), and O'Driscoll (1960), and subsequently modified by Firman (1964, 1973), Harris (1966), Forbes (1983), and Lindsay

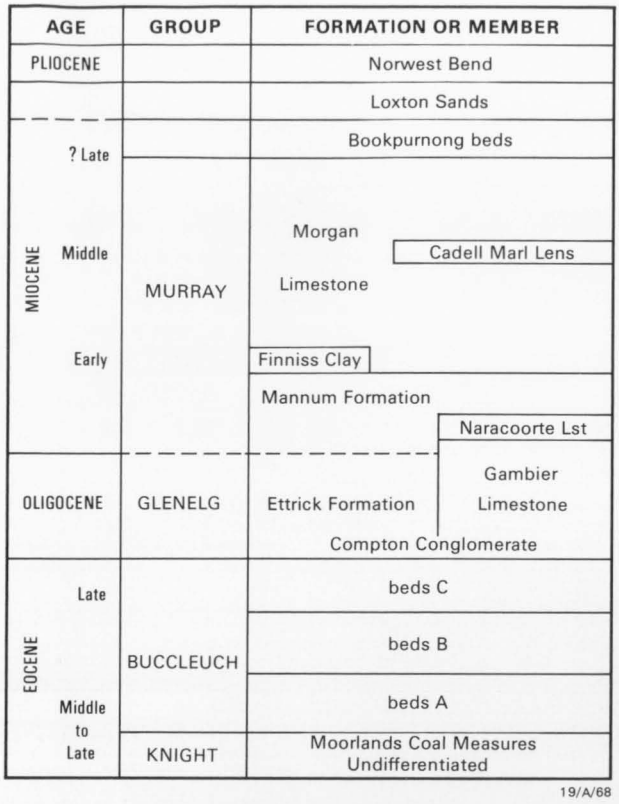


Fig. 42. Tertiary stratigraphy of Murray Basin in South Australia (from Ludbrook, 1961a); note that Knight Group is now known as Renmark Group ('Renmark Beds' of Harris, 1966), and that Loxton Sands included the then undifferentiated Parilla Sand of Firman (1966c, 1973).

(1983a). The South Australian Tertiary scheme (Fig. 42) is partly biostratigraphic in emphasis, and several of the Oligocene–Miocene limestone units, for example, are defined largely on the basis of their micropalaeontological assemblages. In contrast, the Tertiary stratigraphic scheme devised for the subsurface in Victoria (Fig. 43; Lawrence, 1966, 1975; Macumber, 1973, 1978a,b, 1983; Lawrence & Abele, 1976, 1988) is largely lithostratigraphic in character and was developed during the course of hydrogeological investigations. In New South Wales, the Tertiary scheme (Fig. 44) of Woolley & Williams (1978) is largely an adaptation of the Victorian scheme.

The Upper Tertiary and Quaternary stratigraphy of the Murray Basin in South Australia is largely based on the work of Firman (1967a,b, 1969a, 1973), whereas the stratigraphy of surficial morphostratigraphic units in the New South Wales and Victorian sections of the basin is based on modification of the work of Butler (1958), Churchward (1960, 1961, 1963a,b), Lawrence (1966, 1975, 1976a, 1988a), Butler & others (1973), and Bowler & Magee (1978). A diagrammatic representation of the Quaternary stratigraphy of the basin is shown on Figure 46.

The letter symbols in brackets used throughout the text of this Bulletin, correspond to the symbols used in accompanying figures, tables, and enclosed maps, and denote particular stratigraphic units.

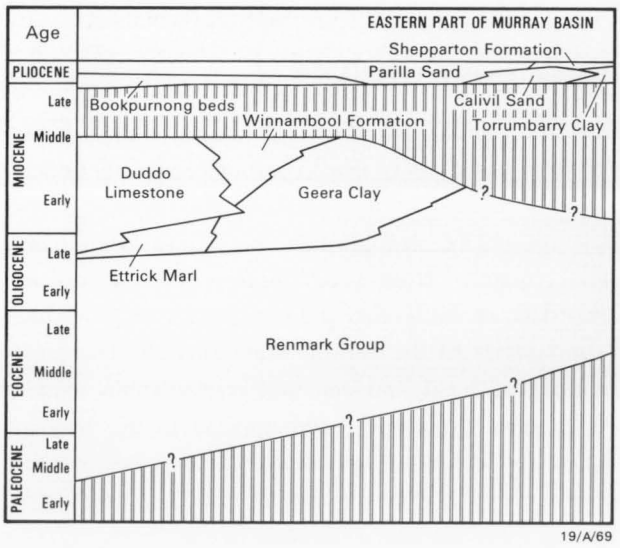


Fig. 43. Tertiary stratigraphy of Murray Basin in Victoria (from Lawrence & Abele, 1976).

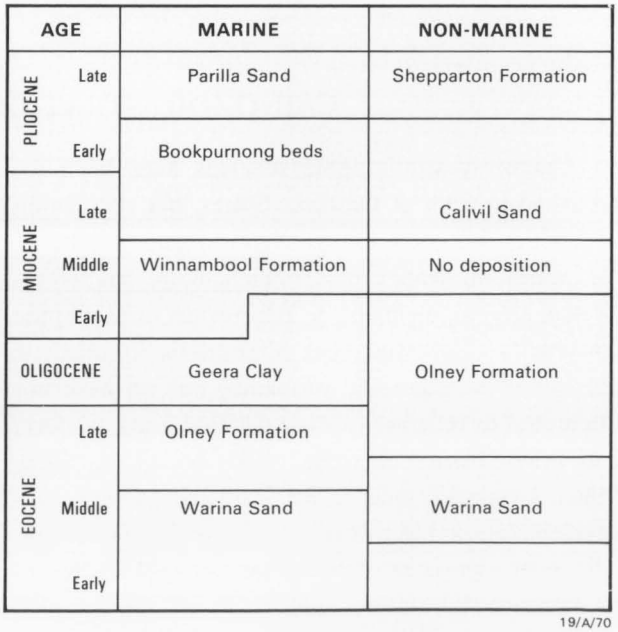


Fig. 44. Tertiary stratigraphy of Murray Basin in New South Wales (from Woolley & Williams, 1978).

Tertiary sediments

The shallow-marine and fluvial units comprising the Tertiary succession of the Murray Basin form an extensive but relatively thin cover of sediment, with a maximum thickness of 600 m within the deeper, west-central part of the basin. Beneath northern, eastern, and southern areas, the succession is generally less than 200–300 m thick. Within the succession at least three major Tertiary depositional sequences have been identified, each consisting of a package of genetically related formations (Fig. 45; Brown, 1983, 1985). Paleocene–Eocene to Lower Oligocene sediments are characteristically carbonaceous and predominantly non-marine, with only minor marine intercalations in the southwest and towards the top in western areas (N.B. Paleocene–Eocene sands at the base possibly form a separate depositional sequence). An Oligo-Miocene sequence consists of marine platform carbonate sediments in the west, and non-marine carbonaceous sand silt and clay in the east and north. An Upper Miocene–Pliocene sequence consists of siliclastic marine sediments in the west, flanked by further non-marine sediments in the east and north. The geological history and interrelationships between tectonic, eustatic and palaeoclimatic influences on sedimentation are discussed in the section on 'Cainozoic Sedimentation Patterns' in Chapter 14. The stratigraphy of the major Tertiary units is summarised on Table 10.

Paleocene–Eocene–Lower Oligocene sequence

At the base of the Tertiary succession (Fig. 45), deep bores drilled into the central-western parts of the Murray Basin (listed in Microform Appendix 2 of Brown & Stephenson, 1986) have encountered a fluvial unit of weakly consolidated medium to coarse quartz sand, with minor intercalated carbonaceous fine sand silt and clay (Tew – Warina Sand of the Renmark Group, Ter; Tew includes equivalent 'Lower Renmark beds' in South Australia; Harris, 1966; Thornton, 1974; Lawrence, 1975). Palynological evidence suggests that this unit is mainly of ?Paleocene–Eocene age. Borehole logs indicate that it consists of massive multistorey sand bodies that coalesce to form a sand sheet which is locally up to 200 m thick, and is mainly restricted in distribution to central-western parts of the basin. Thinner basal sands of uncertain age, which underlie west-central areas of the Riverine Plain, have also been tentatively assigned to the Warina Sand.

Numerous boreholes indicate that the Warina Sand is overlain by a much more widely distributed blanket of unconsolidated, thinly bedded carbonaceous silt, sand, and clay, with common interbeds of lignitic coal and peat (Teo – Olney Formation of the Renmark Group, Ter; and synonymous 'Upper Renmark beds' in South Australia; Harris, 1966; Pels, 1969a; Lawrence, 1975; Woolley, 1978; Woolley & Williams, 1978). The formation extends across most of the Murray Basin and is characterised by the abundant presence of carbonised and pyritised plant remains. The Olney Formation appears to conformably overlie the Warina Sand, but the exact relationship between the two units is unclear owing to poor age control within the basal sandstone unit. Deposition of the Olney Formation was restricted to the Eocene–Early Oligocene in the west, but continued into the Middle Miocene in the north and east. Sedimentation during this extended period (Eocene to Middle Miocene) was probably intermittent, and the succession contains a number of stratal breaks, including a prominent hiatus in the late Early Oligocene (or possibly early Late Oligocene). Oligocene–Miocene sediments of the Renmark Group are, however, lithologically indistinguishable from Eocene–Lower Oligocene sediments, and therefore the variously dated components are herein regarded as parts of a single lithologically distinct unit (Olney Formation).

The Olney Formation is thought to have been deposited predominantly in fluvio-lacustrine environments, but micropalaeontological evidence from several petroleum exploration wells and stratigraphic bores (e.g. Lindsay & Bonnett, 1973; Lawrence & Abele, 1976, 1988; Lindsay 1985a; Brown & Stephenson, 1986; Macphail, 1988a,b; Macphail & Truswell, 1988, 1989) indicates that paralic and minor marine components are increasingly prevalent towards the top of the Olney Formation in western and southwestern areas. In the southwest, water-bores in PINNAROO and NARACOORTE indicate that these components are intercalated with Upper Eocene (to Lower Oligocene) shallow-marine glauconitic calcareous clay, local thin bryozoan limestone, and minor carbonaceous sand which are differentiated as the Buccleuch beds (Teb; Ludbrook, 1961a). Deposition of the Buccleuch beds was mainly confined to a palaeogeographic feature, known as the Buccleuch Embayment (see Fig. 55), although 'Buccleuch beds equivalents' (marine sediments lacking carbonates and lithologically similar to the Olney Formation) have been locally identified in

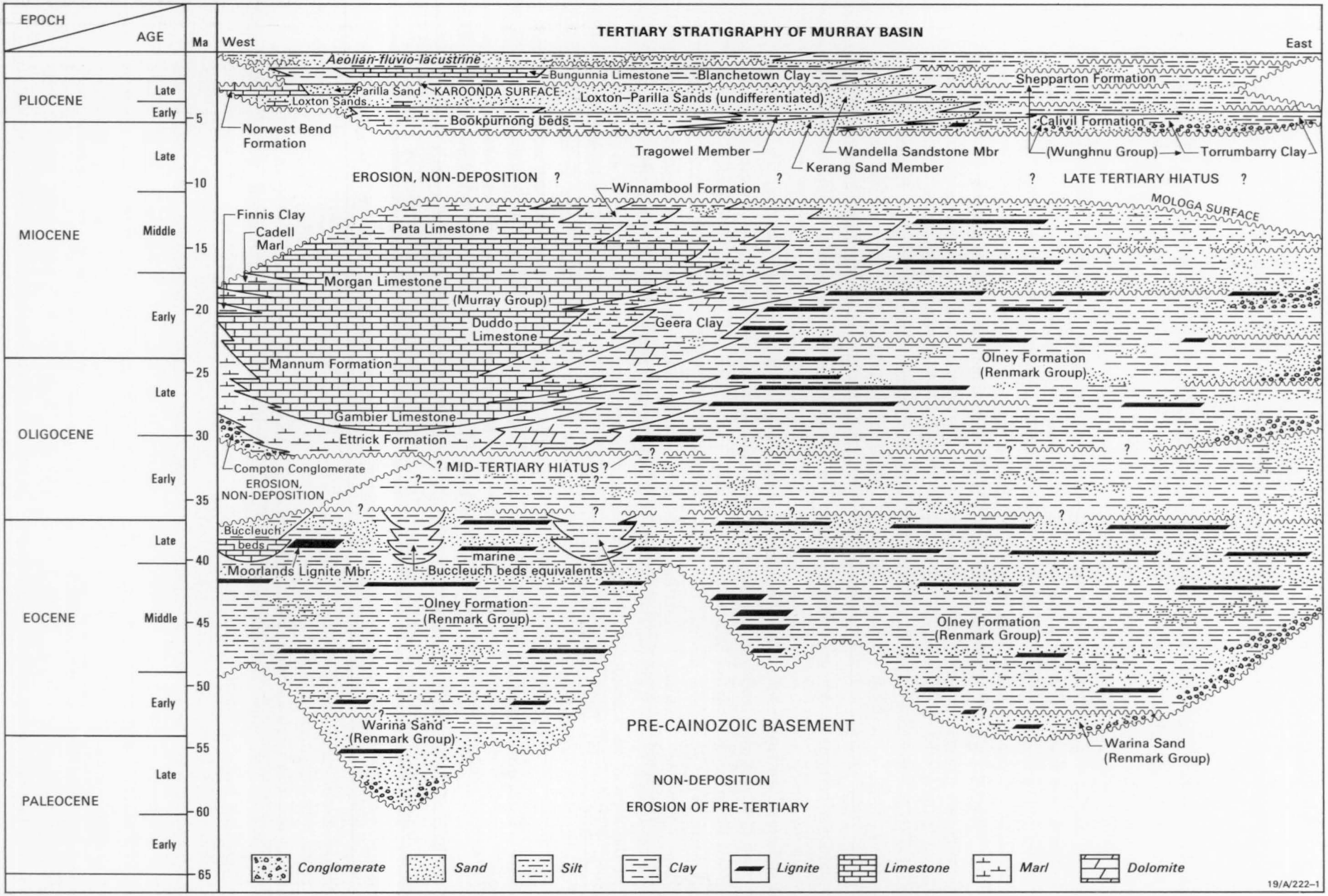


Fig. 45 Tertiary stratigraphy of the Murray Basin.

TABLE 10. TERTIARY STRATIGRAPHIC UNITS OF THE MURRAY BASIN (page 1 of 3)

Age	*Unit*	*Lithology*	*Thickness*	*Distribution & Landform*	*Remarks*
Pliocene to Quaternary	Shepparton Formation (TQs) of Wunghnu Group	Unconsolidated to poorly consolidated mottled variegated clay, silty clay with lenses of coarse to fine polymictic sand & gravel; partly modified by pedogenesis, forming intercalated red-brown palaeosols	100 m mainly < 70 m	Forms extensive flat alluvial flood plains traversed by remnant traces of inactive meandering palaeochannels; underlies Riverine Plain in E.; extends to W. around northern flanks of Victorian highlands, & underlies veneer of aeolian sand around northern fringes of basin	Unconformable over pre-Cainozoic basement rock at basin margins; locally disconformable & unconformable over Teo; conformable over, & locally interfingers with Tpc; interfingers with & locally overlies Tps; disconformable to unconformable under Qdw, Qdp, Qa, Ql, Qdl, Qad; deposited in fluvio-lacustrine, flood-plain, channel, & levee environments; minor aeolian component
Late Tertiary to Quaternary	'Newer Volcanics' (TQv)	Basaltic lava, agglomerate, scoria, tuff, & related volcaniclastic sediments	?	Extensive lava & pyroclastic fields in western Vic. contain numerous small remnant cones, plugs, maars; elsewhere in Eastern Highlands, isolated scoriaceous cones, basaltic plugs, & flows occur in highland valleys & form stranded interfluves	Unconformable over variety of Palaeozoic basement rocks, Cretaceous & Cainozoic sedimentary rocks; accumulated during period of widespread subaerial volcanism, with high proportion of products of phreatic eruptions
Late Tertiary to Quaternary	(TQl)	Duricrust of red massive to pisolitic ferruginous subsoil underlain by mottled clay over pallid zone of white kaolinitic clay	< 10 m	Forms residual flat to gently undulating surfaces, locally deeply dissected to form steep-sided remnants; erosional remnants occur throughout flanking highlands, but are particularly extensive over Dundas Tableland, & parts of Mount Lofty & Flinders Ranges	Developed over range of pre-Cainozoic basement rocks (in flanking range) & over Cainozoic sedimentary rocks; 'Karoonda Surface' component overlies Tps & underlies Qpc; composite lateritic duricrust developed over elevated surfaces in environments exposed to deep chemical weathering
Pliocene	Norwest Bend Formation (Tpn)	Partly cemented pale grey, brown, yellow coquinoid limestone with fossiliferous quartz sand matrix; characterised by oyster beds	mainly < 10 m	Exposed in cliffs of R. Murray gorge; elsewhere concealed; confined to areas adjacent to present-day course of R. Murray at western margin of basin	Disconformable & unconformable over Tml; conformable, interfingers with, & unconformable over elements of Tps; disconformable & unconformable under Qpc, Qdw, Qca, Qdm, Qad, Qfr, Qa; deposited in estuarine environment
Late Miocene to Pliocene (mainly Pliocene)	Loxton-Parilla Sands (Tps)	Unconsolidated to weakly cemented yellow-brown fine to coarse well sorted quartz sand, sandstone, with minor clay, silt, pebbly conglomerate; locally includes fine to coarse shelly sandstone, poorly sorted micaceous quartz sand & gravel; marine shell & trace fossils occur in places; locally ferruginised & pyritic; towards top, contains interstitial white kaolinitic or gibbsite clay matrix, locally capped by sandy pisolitic ferruginous duricrust	100 m mainly < 60 m	Forms deflated blanket of sand beneath almost entire S.W. Murray Basin; with remnants of topographically prominent subparallel stranded shallow/marginal-marine ridges with inter-ridge fluvial sediments; estuarine & fluvial components exposed in R. Murray cliffs in W.; fluvial components underlie much of N.W. of basin; mainly concealed	Locally conformable over pre-Cainozoic basement in S.; locally unconformable over Tml, Tmg, Teo; interfingers with & conformably over Tpb; interfingers with & locally conformably over Tpc; interfingers with & locally conformable under TQs; disconformable & unconformable under Qpb, Qpc, Qdw, Qca, Qdm, Qdu, Qly, Qdl, Qa, Ql; composite sand sheet deposited in strand-plain environments — including shallow-marine, beach, & estuarine — flanked & locally overlain by fluvial, fluvio-lacustrine inter-ridge environments
Late Miocene to Early Pliocene	Calivil Formation (Tpc) of Wunghnu Group	Poorly consolidated pale grey, poorly sorted coarse to granular quartz sand, conglomerate, with white kaolinitic matrix; includes thick intercalations of kaolin, thin lenses of carbonaceous clay; grainsize diminishes basinward, where unit includes dark brown ferruginised & grey pyritic sand with minor interbedded carbonaceous silt & clay	100 m mainly < 60 m	Extensive blanket underlies much of Riverine Plain & northern fringes of basin; fills previously eroded entrenchments within older units in adjacent highland valleys to form youngest of several gold-bearing deep-lead systems of northern Vic.; mainly concealed	Locally unconformable over Palaeozoic basement rocks, Pl, Kl; disconformable to unconformable over Teo & locally Tmg, Tmw; interfingers with & locally overlain by Tps; Locally interfingers with Tpb; conformable under & locally interfingers with TQs; Locally unconformable under TQv, Qfr, Qa; deposited in valley-fill, alluvial-fan, fluvio-lacustrine, & braided-channel environments

TABLE 10. (page 2 of 3)

Age	Unit	Lithology	Thickness	Distribution & Landform	Remarks
CAINOZOIC / TERTIARY					
Late Miocene to Pliocene	Bookpurnong beds (Tpb)	Poorly consolidated to plastic brown, greenish grey calcareous clay (marl), silt, sand; highly fossiliferous, glauconitic, micaceous, & locally carbonaceous; characterised by molluscan macrofossils	150 m	Thin blanket underlies central-west of basin; locally exposed on banks of R. Murray in S.A. but almost entirely concealed	Disconformable & locally unconformable over Tml, Tmw, Tmg; interfingers with and conformable under Tps; locally interfingers with Tpc beneath central western Riverine Plain; deposited over shallow/restricted-marine shelf
Late Oligocene to Middle Miocene	Winnambool Formation (Tmw) of Murray Group	Poorly consolidated friable to plastic grey, blue-grey, pale green glauconitic, highly fossiliferous calcareous clay (marl) with intercalated skeletal calcisiltite, calcarenite, & dense micritic limestone; contains abundant well preserved & diverse faunas	110 m mainly <50 m	Entirely concealed; occurs in arcuate zone underlying central-west of basin beneath western Vic. extending into north-central areas in S.A.	Locally disconformable over Teo, to S. & W. interfingers with Toe; conformable under & interfingers with Tml; to N.& E. conformable over, interfingers with, & locally conformable under Tmg, Teo; disconformable under Tpb, Tps; deposited in restricted-marine platform & lagoonal environments
Late Oligocene to Middle Miocene	Murray Group limestone units (Tml)	Consolidated well bedded pale grey, yellow, white, cream coarse to medium, highly fossiliferous skeletal calcarenite, calcareous-cemented quartz sandstone, bioclastic limestone, micritic limestone, weakly consolidated calcareous clay (marl); characterised by abundant fragmented skeletal debris of diverse, mainly temperate-water foramol, fossil assemblages	150 m	Underlies central-west & S.W. of basin; mainly concealed but forms cliffs of R. Murray gorge; minor karstified outcrops in S.W.	Includes Gambier Limestone, Mannum Formation, Morgan Limestone, Pata Limestone (S.A.), Duddo Limestone (Vic. & N.S.W.); Finniss Clay & Cadell Marl intercalated within Tml; in S.W. Tml locally unconformable over pre-Cainozoic basement; locally disconformable over Eocene Teo, Teb; conformable over & locally interfinger with Toe, Toc; to N. & E. conformable over, interfingers with, & locally conformable under Tmw, Tmg; disconformable & locally unconformable under Tpb, Tps, Tpn; unconformable under Qpl, Qpb, Qca, Qdw, Qdm, Qad, Qa; deposited over shallow-marine platform
Late Oligocene to Middle Miocene	Geera Clay (Tmg) of Murray Group	Poorly consolidated plastic to friable black, grey, dark green silt, clay, minor sand; commonly glauconitic, fossiliferous, calcareous, carbonaceous; locally includes sandy dolomitic intercalations; contains abundant low-diversity faunas	170 m mainly <50 m	Entirely concealed; occurs in arcuate zone underlying western Vic. & northwestern areas in N.S.W. & S.A.	To E & N conformable over & interfingers with Oligo-Miocene components of Teo; to S.W. conformable under & interfingers with Toe, Tmw, Tml; locally overlies Tmw, Tml; to N. & ?E. locally conformable under Middle Miocene Teo; disconformable under Tpb & locally Tps; deposited in shallow & marginal marine, interdistributary-bay, lagoonal, & tidal-flat environments
Oligocene to Early Miocene	Ettrick Formation (Toe) of Murray Group	Weakly lithified grey, green glauconitic, highly fossiliferous calcareous clay (marl), silt, sandy skeletal clay, thin micritic limestone intercalations, increasing skeletal calcarenite towards top; lithologically more variable towards base, where includes minor fossiliferous quartz sand, carbonaceous clay; contains abundant & diverse faunas	<30 m	Almost entirely concealed; minor outcrop at S.W. margin of basin; underlies central-west & S.W. of basin, mainly in western Vic. & S.A.	In S.W. disconformable over Eocene Teo, Teb; conformable over Toc; to E & N. conformable over & interfingers with Oligocene components of Teo; interfingers with Tmw, Tmg, Tml; conformable under Tml; deposited in shallow-marine, restricted platform to lagoonal environments

TABLE 10. (page 3 of 3)

Age	*Unit*	*Lithology*	*Thickness*	*Distribution & Landform*	*Remarks*
Oligocene	Compton Conglomerate (Toc) of Murray Group	Lithologically variable; includes partly cemented medium to coarse ironstone & quartz-pebble conglomerate with ferruginised matrix, dark brown humic clay, green glauconitic clay, red clay with pebble clasts, & yellow, brown, grey, poorly fossiliferous calcareous sandstone & clay (marl)	16 m mainly < 10 m	Patchy subsurface distribution in S.W., in S.A.; entirely concealed	Locally unconformable over pre-Cainozoic basement; disconformable over Teo, Teb; conformable under Toe & locally Tml; composite unit deposited in subaerial residual & associated transgressive shallow-marine environments
Late Eocene to Early Oligocene	Buccleuch beds (Teb)	Poorly consolidated grey-brown carbonaceous clay with limonitic upper surface; underlain by friable carbonaceous sand with thin limestone lenses, further underlain by highly fossiliferous white bryozoan limestone with green-grey glauconitic calcareous clay (marl)	78 m mainly < 30 m	Entirely concealed; occurs beneath S.W. of basin in S.A. (possible marine equivalents in deeper central-western areas, but these currently included in Olney Formation	Locally unconformable over Palaeozoic basement; conformably overlies & interfingers with Eocene components of Teo in S.W.; disconformably to unconformably overlain by Teo, Toe, & locally by Tml, Qpl; deposited in shallow-marine to paralic environments
Paleocene to Miocene	Renmark Group (Ter):				Component formations Warina Sand & Olney Formation
Eocene to Middle Miocene	Olney Formation (Teo) of Renmark Group (Ter)	Unconsolidated to poorly consolidated, thinly bedded dark brown, grey, black carbonaceous silt, sand, clay, brown coal, peat; commonly micaceous, pyritic, ferruginised; includes intercalations of poorly sorted fine to medium quartz sand, polymictic sand, sandy dolomite	200 m	Forms virtually continuous but thin blanket beneath almost entire Murray Basin; absent beneath basin margins & over some buried basement ridges; entirely concealed within basin, but possible equivalents exposed in valley of Glenelg R. to S. & as erosional remnants in adjacent areas of Victorian highlands	Includes 'Upper Renmark beds' in S.A.; basal unit of much of basin & unconformable over variety of pre-Cainozoic basement rocks, TRs, Pu, Pl, Kl; ?conformable or ?disconformable over Tew; in S.W. Eocene components conformable under & interfinger with Teb, disconformable under Toc, Toe, Tml, Tmg; to E. & N. Oligo-Miocene components conformably overlain by & interfinger with Toe, Tmw, Tml, Tmg; Middle Miocene components locally conformable over Tmg & locally disconformable under Tps, Tpb; in E. & N. disconformable & locally unconformable under Tpc, TQs; can be correlated with Ta of highland valleys; deposited in fluvio-lacustrine, meandering-channel, flood-plain, & swamp environments; towards top; in W. includes deltaic, paralic sediments
Paleocene to ?Early Eocene	Warina Sand (Tew) of Renmark Group (Ter)	Unconsolidated loose to friable grey, brown, poorly to well sorted medium to coarse quartz sand with minor intercalated fine sand, silt, clay, carbonaceous clay	200 m	Confined in distribution to deeper western & central areas; entirely concealed	Basal unit of restricted distribution & unconformable over pre-Cainozoic basement rocks, Pl, Kl; ?conformable or ? disconformable under Teo; includes 'Lower Renmark beds' in S.A.; fluvial
Paleocene to Miocene	'Older Volcanics' (Tv)	Basaltic lava, agglomerate, tuff, small basalt plugs, dykes, associated volcaniclastic sediments	highly variable	Numerous small but widespread valley flows & hill-top cappings occur in highlands flanking southern & eastern Murray Basin	Unconformable over variety of pre-Cainozoic metasediments, granites & volcanics; deposited as subaerial volcanics
Undifferentiated Tertiary	(Ta)	Unconsolidated to locally ferruginised, silicified, poorly sorted pebble to boulder conglomerate, granular to fine sand with sandy clay or kaolinitic matrix, minor silt, clay, kaolin intercalations	locally up to 100 m	Occurs throughout highlands flanking basin; erosional remnants exposed in highland valleys & stranded interfluves	Unconformable over variety of Palaeozoic basement rocks; high-level residual, valley-fill, alluvial, & colluvial sediments; can be partly correlated with Tew/Ter

western and west-central areas.

Oligocene–Middle Miocene sequence

A marine transgression in the late Early-Oligocene resulted in deposition of the marine and marginal-marine formations of the Oligocene to Middle Miocene Murray Group. To the east and north, these grade laterally into the predominantly non-marine sediments of the Renmark Group (younger components of the Olney Formation). The Oligocene Compton Conglomerate (Toc) occurs at the base of the Murray Group, but is patchy in distribution and lithologically variable, consisting of residual quartz-pebble conglomerate with a ferruginous matrix as well as shallow-marine glauconitic clay and poorly fossiliferous sandstone. In most areas, however, Oligocene glauconitic calcareous clay (marl) of the Ettrick Formation (Toe; Ludbrook, 1961a) forms the basal unit of the Oligo-Miocene sequence. This is succeeded up-sequence by Upper Oligocene to Middle Miocene shallow-marine platform limestones, consisting of coarse-grained skeletal debris admixed with varying proportions of quartz sand, micrite and calcareous clay (Tml – Gambier Limestone, Mannum Formation, Morgan Limestone, Pata Limestone, Duddo Limestone; Ludbrook, 1957, 1961a, 1963a; Lindsay & Bonnett, 1973; Lawrence, 1975). These platform limestones are calcarenitic, with minor calcareous sandstone, in the west, and are increasingly micritic to the southeast. To the north and east, the platform limestones grade into a narrow zone of glauconitic calcareous clay and thin limestone of the Winnambool Formation (Tmw; Lawrence, 1975), deposited in restricted-platform and lagoonal environments. The Winnambool Formation is essentially a younger diachronous equivalent of the lithologically similar Ettrick Formation. These calcareous clay units in turn grade laterally into the Geera Clay (Tmg; Lawrence, 1975; Lawrence & Abele, 1976, 1988). This consists of black, locally carbonaceous, silty quartz-rich mud and clay with minor dolomite, and minor sand intercalations. It was deposited in shallow to marginal-marine environments – including extensive interdistributary-bay and tidal-flat settings. To the north and east, the Geera Clay in turn interfingers with deltaic and fluvio-lacustrine silt, sand, clay, and peaty coal (additional Teo – Olney Formation). As noted above, these Oligocene–Middle Miocene fluvial sediments are lithologically indistinguishable from the underlying Eocene–Lower Oligocene fluvial sediments, and hence are included in the Olney Formation.

During the subsequent retreat of the sea from the basin in the Mid-Miocene, the Olney Formation, the Geera Clay and the Winnambool Formation appear to have partly prograded back over the top of the platform limestones, so that the Geera Clay partly envelops the marls, which in turn partly envelop the limestones. Deposition of the platform carbonates and associated terrigenous clastics of the Murray Group appears to have ceased by the late Middle Miocene.

Upper Miocene–Pliocene sequence

A further short-lived marine transgression–regression over southwestern areas can be correlated with deposition of the last major Tertiary depositional sequence of the basin in the Late Miocene–Pliocene (Brown, 1983, 1985; Carter, 1985). At the base of the sequence, the Upper Miocene Bookpurnong beds (Tpb) consist of clay and marl deposited, over a disconformity, in shallow-marine environments. These are flanked to the north and east by marginal-marine sand of the basal undifferentiated Loxton–Parilla Sands (Tps). They consist of the basal Loxton Sands in South Australia and the stratigraphically equivalent (and lithologically similar) basal Parilla Sand in Victoria and New South Wales (N.B. the name Parilla Sand, as defined in South Australia is restricted to younger cross-cutting fluvial deposits, but the name has also been widely applied in Victoria and N.S.W. to sands which are predominantly equivalent to the Loxton Sands of S.A. – see 'Loxton–Parilla Sands'; Brown, 1985; Carter, 1985; Brown & Stephenson, 1986). The basal Loxton–Parilla Sands are in turn flanked to the east and north by Upper Miocene–Lower Pliocene coarse-grained quartzose sand and gravel of the fluvial and fluvio-lacustrine Calivil Formation. These form an extensive sand sheet underlying much of the eastern and northern Murray Basin (Tpc; Lawrence & Abele, 1976, 1988; Macumber, 1978a). The Calivil Formation also infills concealed entrenchments within older sediments and basement rocks of adjacent highland valleys; in northern Victoria the unit forms the youngest of several Tertiary gold-bearing 'deep-lead' placer systems (e.g. Hunter, 1909; Macumber, 1978a,b).

Much of the western Murray Basin is underlain by an extensive sand sheet deposited during the final retreat of the sea from the basin in the Pliocene (further undifferentiated Loxton–Parilla Sands of Tps). It consists of a composite of upper Loxton Sands and Parilla Sand (S.A. terminology) and Parilla Sand

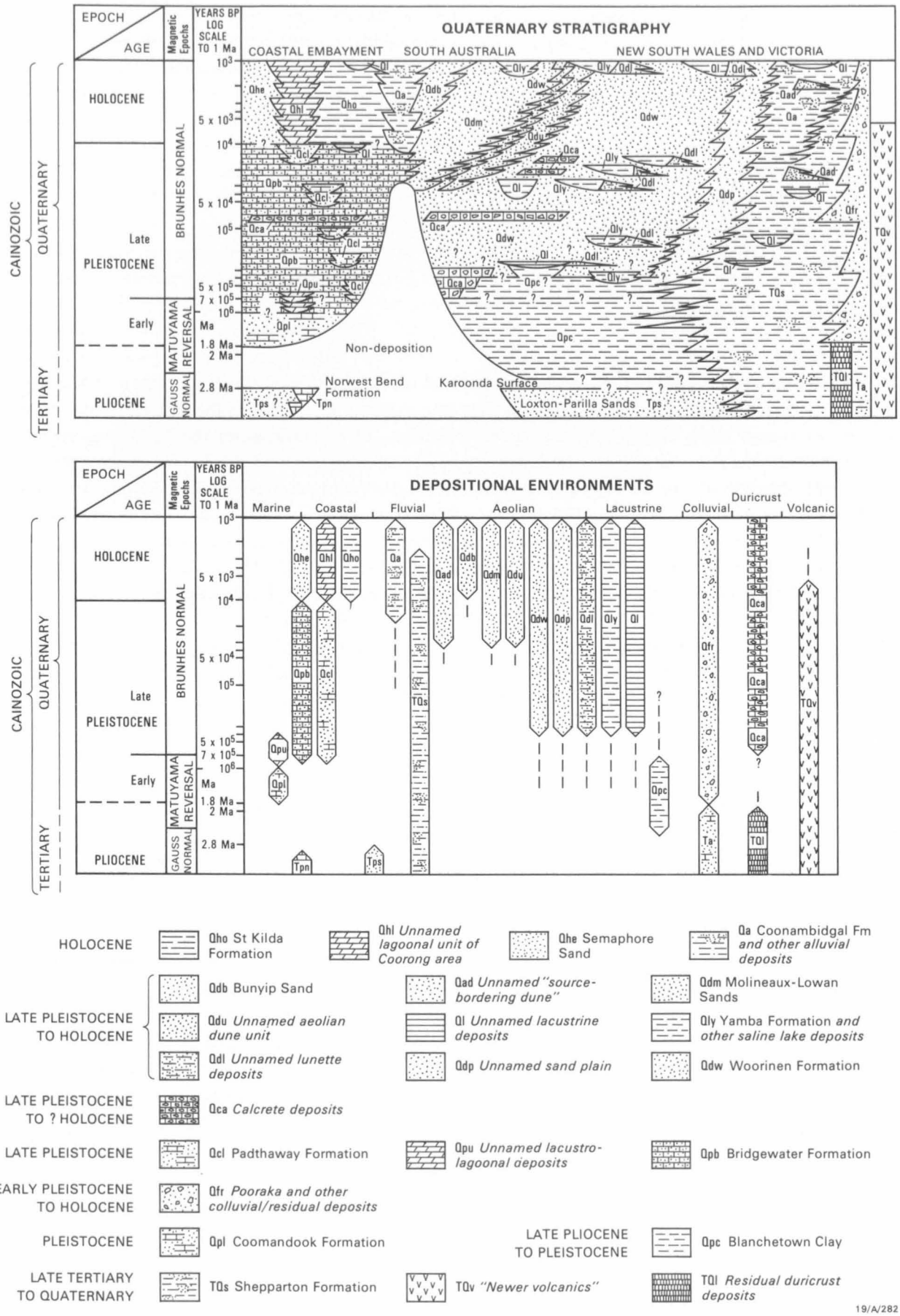


Fig. 46. Stratigraphic relationships and depositional environments of the Quaternary units of the Murray Basin.

(Victorian terminology; Fig. 43); Ludbrook, 1961a; Firman, 1973; Lawrence, 1975; Macumber, 1978a; Brown, 1983, 1985; Carter, 1985). The sand sheet consists of various shallow-marine, lower shore-face and beach quartz sand deposits, as well as younger inter-ridge and cross-cutting, fluvial and estuarine deposits, which together formed a composite strandplain deposit. A prominent surface characteristic of the composite unit is the presence of stranded shallow-marine, beach-ridge and associated swale complexes in western Victoria and adjacent areas of South Australia. Several generations of cross-cutting and disconformable estuarine and fluvial deposits dominate the succession exposed along the Murray River Gorge in the west. At the western margin of the basin, estuarine oyster beds of the Norwest Bend Formation (Tpn; Ludbrook, 1961a) were deposited during a subsequent minor rise in sea-level in the Late Pliocene (Twidale & others, 1978). In the east, the Pliocene regression can be correlated with deposition of fine-grained clastics and polymictic sand and gravel of the Pliocene to Quaternary Shepparton Formation, by aggradation in a predominantly flood plain-environment (TQs; Lawrence, 1975).

Quaternary sediments

In the east and north of the Murray Basin, aggradational fluvio-lacustrine sedimentation continued intermittently throughout the Quaternary (additional TQs – Shepparton Formation; Lawrence, 1975; Fig. 46), resulting in development of the modern flat-lying Riverine Plain (Butler & others, 1973). Farther west, the Tertiary is partly overlain by a thin veneer of Pleistocene fluvio-lacustrine clay (Qpc – Blanchetown Clay; Firman, 1973; Lawrence, 1975), further overlain by an arid and semi-arid landscape of Upper Pleistocene–Holocene aeolian dunefields (Qdw – Woorinen Formation; Qdm – Molineaux Sand in South Australia (Firman, 1973) and Lowan Sand in Victoria (Lawrence, 1975, 1980; Bowler & Magee, 1978). Surface drainage is almost entirely absent in the west, apart from the entrenched courses of the Murray and Darling Rivers (see Chapter 3). Farther east, the Riverine Plain is drained by the extensive distributary networks of the Murray, Murrumbidgee, Lachlan, Ovens, Goulburn, and Loddon Rivers. Fluvial sedimentation continues within the confined floodplains of these modern rivers (Qa – Coonambidgal Formation and other undivided alluvial deposits), which are entrenched within older fluvial and aeolian landscapes.

Small but numerous and widely distributed Upper Pleistocene–Holocene lacustrine surficial units are also present throughout the Murray Basin (Ql – lacustrine clays; Qly – Yamba Formation and other undivided saline lake deposits). Lunette deposits (Qdl) are associated with former and present-day lakes. Small areas of fluvial-derived aeolian dune deposits (Qad – 'source bordering dunes') occur adjacent to both relict and active river channels. At the margins of the basin, coarse colluvial and alluvial deposits form extensive coalesced fans, talus cones, and scree slopes (Qfr – Pooraka Formation and other undivided colluvial and residual accumulations). Many of these surficial units are essentially morphostratigraphic in character, rather than conventionally lithostratigraphic (Brown & Stephenson, 1985).

In coastal areas, Quaternary deposits include shallow and marginal-marine sediments (Qpl – Coomandook Formation; Qpu – unnamed algal dolomites), a number of prograding beach-ridge and dune complexes (Upper Pleistocene Qpb – Bridgewater Formation; Holocene Qhe – Semaphore Sand), and back-ridge lagoonal and inter-ridge fluvial and lacustrine sediments (Upper Pleistocene Qcl – Padthaway Formation; Holocene Qho – St. Kilda Formation).

The Quaternary geology and complex morphostratigraphy of the basin have been extensively studied, and summaries have been published by Butler & others (1973), Firman (1973), Lawrence (1976a, 1988a), Bowler & Magee (1978), and Twidale & others (1978), and in various papers in both Storrier & Kelly (1978), and Storrier & Stannard (1980). The stratigraphy of the major Quaternary units is summarised in Table 11.

CAINOZOIC

QUATERNARY

TABLE 11. QUATERNARY STRATIGRAPHIC UNITS OF THE MURRAY BASIN (page 1 of 4)

Age	*Unit*	*Lithology*	*Thickness*	*Distribution & Landform*	*Remarks*
Holocene	St. Kilda Formation (Qho)	Unconsolidated mud, silt, sand, shell debris; minor ephemeral salt crusts of gypsum, halite	3 m	Forms littoral lake complexes, partly emergent estuarine flats, & salinas; occurs in Lake Alexandrina area at mouth of Murray R. & in other coastal lakes of S.E. S.A.	Surficial morphostratigraphic unit; unconformable over Qpb; interfingers with Qhe, Qhl, Qa; disconformable over Qpu; deposited in estuarine, coastal lake, & swamp environments
Holocene	(Qhl)	Unconsolidated to weakly lithified fossiliferous micritic & dolomitic mud, dolomite; minor quartz sand, clay, shell detritus, calcareous algal biolithite	6 m mainly 1-2 m	Locally exposed around margins of Coorong & other coastal lake complexes	Surficial morphostratigraphic unit; disconformable over Qpb; interfingers with Qhe, Qho; deposited in restricted, brackish to marine, lagoonal environments
Holocene	Semaphore Sand (Qhe)	Unconsolidated, locally mobile white calcareous fossiliferous quartz sand; minor humic debris, calcareous rhizoliths	30 m mainly 5 m	Forms present-day coastal beach & dune complexes, forming barrier separating Coorong from Southern Ocean	Morphostratigraphic unit; disconformable over Qpb; interfingers with Qhl, Qho; deposited in coastal beach & associated aeolian dune environments
Late Pleistocene to Holocene	Coonambidgal Formation of Wunghnu Group & other alluvial deposits (Qa)	Unconsolidated grey, brown micaceous silty clay, silt, polymictic sand, gravel	25 m	Forms flat low-lying deposits in narrow meander belts, anastomosed distributaries, & confined flood plains; occurs in widely distributed active & recently active channels incised within older fluvial sediments of Riverine Plain & adjacent tributary highland valleys; in W. occurs in flood plains of Murray & Darling Rivers & in areas of internal drainage within aeolian landscape	Unconformable over Pre-Cainozoic basement rocks, Cainozoic sediments & volcanics in flanking highlands; incised within TQs of Riverine Plain & Qdw, Qdp, Qdu of Mallee region, & Tps, Tpb, Tml, in Murray R. gorge; associated with Qad, Qdb, Ql; interfingers with younger components of Qfr; deposited in fluvial, fluvio-lacustrine, channel, & flood-plain environments of existing river systems
Late Pleistocene to Holocene	Bunyip Sand (Qdb)	Unconsolidated, locally mobile pale red-brown quartz sand; minor calcareous rhizoliths	5 m	Forms elongate hummocky dunefields E. of & adjacent to Murray R. in S.A.	Morphostratigraphic unit; disconformable to unconformable over Qca, Qdw, Qpc, Tps, Tpn, Tml; associated with Qa of Murray R. gorge; deposited in fluvial-derived source-bordering aeolian dune complexes
Late Pleistocene to Holocene	(Qad)	Unconsolidated, locally mobile pale orange, yellow siliceous sand; locally includes abundant micaceous & lithic grains	locally up to 20 m	Forms elliptical mounds & elongate hummocky dune complexes adjacent to active & former river channels; widely distributed throughout Riverine Plain; in W., occurs on E. (leeward) side of channels in Murray & Darling drainage systems	Morphostratigraphic unit associated with TQs & Qa; deposited as fluvial-derived source-bordering aeolian dune complexes
Late Pleistocene to Holocene	Molineaux-Lowan Sands (Qdm)	Unconsolidated, locally mobile, yellow, grey, pale orange well sorted medium to fine frosted quartz sand; in S.W., includes marine-derived calcareous skeletal aeolianite; older components weakly modified by pedogenesis contain minor calcareous filamental rhizoliths, calcrete glaebules, iron-cemented pisoliths	20 m mainly < 10 m	Forms irregular to subparabolic, locally linear sharp-crested, densely packed dunes with narrow interdune corridors & minor sand plains; occurs within extensive, easterly trending tongue-like dunefields extending from coastal areas & E. of Murray R. in S.A. into western Vic., where it forms Sunset Desert, Big Desert, & Little Desert	Unconformable over Tps & locally over Tml; disconformable over Qpc, TQs, Qpb, Qcl, Qpu, Qdp, Qdw, Qca; overlies & interfingers with Qa, Qly, Ql, Qdl,Qfr, Qho; locally overlain by Qa, Ql, Qly, Qdl; morphologically similar & transitional with Qdu & younger components of Qdw; deposited in aeolian dune environment
Late Pleistocene to Holocene	(Qdu)	Unconsolidated, locally mobile red-brown, pale orange siliceous sand; consists of medium to fine quartz grains admixed with humic debris & fragmented calcareous & gypsic filamental rhizoliths; weakly modified by pedogenesis	20 m mainly < 10 m	Forms sharp-crested irregular to subparabolic, locally linear dunes with narrow interdune depressions; occurs within elongate, easterly trending dunefields; occurs in N.W. (mainly E. of Darling R.) & W. of Riverine Plain	Unconformable to disconformable over Tps, Qpc; transitional with Qdw, Qdp, Qdm; overlies, interfingers with, & unconformably to disconformably overlain by Qly, Qdl, Ql, Qa; deposited in aeolian dune environment

TABLE 11. (page 2 of 4)

Age	Unit	Lithology	Thickness	Distribution & Landform	Remarks
CAINOZOIC / QUATERNARY					
Late Pleistocene to Holocene	(Ql)	Friable to plastic, finely laminated grey clay, silty clay, humic clay, grey palaeosols; locally includes medium to fine sand	< 10 m	Occurs in flood-plain lakes & swamps, interdune deflation hollows, & coastal lake complexes; widely distributed throughout fluvial & aeolian landscapes of basin, but mainly associated with active & recently active flood plains of Riverine Plain; forms extensive lake complexes associated with Darling R., Darling Anabranch, & Willandra Creek system	Morphostratigraphic unit associated mainly with TQs, Qa; interfingers with Qdl; interfingers with, & unconformable to disconformable over TQs, Tps, Qpc, Qa, Qdw, Qca, Qdp, Qdm, Qdu, Qly; deposited in lacustrine & associated strand-line environments
Late Pleistocene to Holocene	Yamba Formation & other saline lake deposits (Qly)	Friable pale grey gypsite, gypsiferous clay with selenite crystals, grey pelletal gypsum-quartz sand aggregates; locally includes grey clay with crystalline gypsum mush under black sulphide-rich mud with ephemeral salt crusts of gypsum, halite, bischofite, thenardite, mirabilite; in places associated with mounds & sheets of quartz sand cemented by ferricrete, calcrete, & silcrete	< 10 m	Forms aeolian-modified gypsite flats; active salinas occur in topographic lows as irregularly shaped lake complexes entrenched within relict pedestals of former lake floors; mainly occurs in association with active & relict terminal lakes & groundwater discharge zones entrenched within aeolian landscape in W.; relict deposits occur in N.; active salinas also occur adjacent to coast	Unconformable to disconformable over Tps, TQs, Qpc; interfingers with Qdl; locally associated with Ql; locally disconformable under, interfingers with, & overlies Qdw, Qca, Qdp, Qdm, Qdu, TQs, Qa; deposited in lacustrine, evaporitic, & aeolian environments of ephemerally active playas maintained by groundwater discharge & by deflation of lake floors
Late Pleistocene to Holocene	(Qdl)	Poorly consolidated brown, red, yellow, grey siliceous sand, silty clay, clay-pellet aggregates, gypsic clay pellets, pale grey gypsite; older components increasingly modified by pedogenesis include intercalated red calcareous & gypsiferous palaeosols with calcrete glaebules, rhizoliths; locally capped by white mobile well sorted quartz sand	up to 40 m	Forms single & multiple lunettes (crescentic, transverse dunes), concave to W., located on E. side of lake basins; locally flanked by blowout dunes of mobile white sand; widely distributed throughout basin but particularly well developed adjacent to lakes of Darling R. & Darling Anabranch & former lakes of Willandra Creek system	Unconformable to disconformable over Tps, TQs, Qpc; mainly interfingers with Qly, Ql; locally underlies, interfingers with, & overlies Qdw, Qca, Qdp, Qdu, Qdm, TQs, Qa; deposited in aeolian dune environment adjacent to deflated lake floors & shores
Late Pleistocene to Holocene	(Qdp)	Unconsolidated red, brown clayey siliceous sand & clay-pellet aggregates admixed with loamy soils; sand component consists of medium to fine quartz grains with red clay cutans; modified by pedogenesis, forming iron & carbonate-cemented nodules grading to calcrete hardpans	mainly < 3 m	Forms extensive flat to gently undulating plains; locally with numerous fluvio-lacustrine depressions, particularly in N.; includes narrow aeolian-modified sand plains adjacent to rivers & lakes of Darling R. system	Unconformable to disconformable over Tps, TQs, Qpc; overlies & intercalated with Qca; overlies & interfingers with Qfr; transitional with Qdw; locally unconformable under Qa, Ql, Qly, Qdl; deposited in aeolian sand sheet & associated lacustrine & claypan environments

TABLE 11. (page 3 of 4)

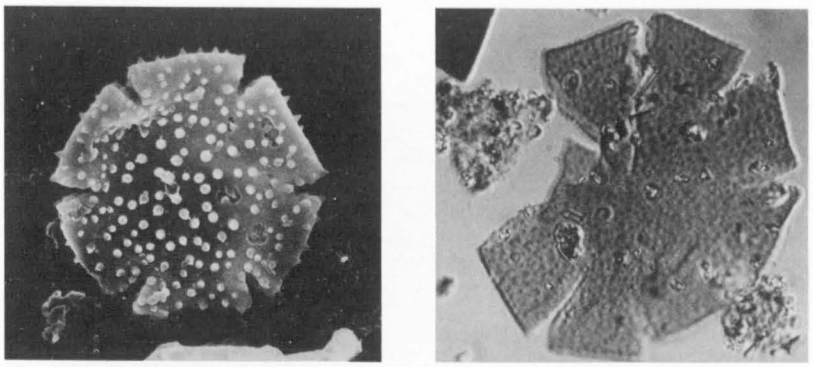
Age	*Unit*	*Lithology*	*Thickness*	*Distribution & Landform*	*Remarks*
Late Pleistocene to Holocene	Woorinen Formation (Qdw)	Unconsolidated red-brown siliceous silty sand, red calcareous silty clay, sandy clay, clay-pellet aggregates; sand component consists of medium to fine quartz grains with red clay cutans admixed with humic debris & fragmented calcareous tap-root & filamental rhizoliths; partly modified by pedogenesis, forming intercalated red calcareous palaeosols with gypsiferous & soft to resistant carbonate glaebules, grading to cemented calcrete hardpans which locally form massive brecciated sheets	2-3 m dunes thicker	Forms extensive dunefields of discontinuous E.- W. oriented dunes with subdued crests & flanks separated by broad swales & sand plains; widely distributed; underlies much of aeolian Mallee landscape of western Murray Basin	Unconformable to disconformable over Tps, & also Tml, Tpn, TQs,Qpc; underlain & intercalated with Qca; overlies & interfingers with Qfr, & older components Qly; transitional with Qdm, Qdu; locally unconformable under younger Qly, Qa, Qad, Qdb; deposited in aeolian dune & swale environments
Early to Late Pleistocene	Padthaway Formation (Qcl)	Unconsolidated sand, silt, sandy variegated clay, peat, calcareous clay (marl), freshwater limestone	50 m mainly in range 5-20 m	Occurs in coastal areas of S.E. S.A., where forms widespread low-lying plains & wetlands with minor lunettes	Interfingers with & conformable over Qpb; unconformable under Qca, Qdm; disconformable to conformable under Ql, Qho, Qhl, ?Qhe; deposited in lacustro-lagoonal, swamp, minor lunette, & locally colluvial environments between stranded beach ridges
Early to Late Pleistocene	Bridgewater Formation (Qpb)	Poorly consolidated pale yellow, pinkish brown fine to coarse fossiliferous calcareous sand, calcarenite; locally capped by calcrete	80 m mainly in range 15-40 m	Forms series of stranded elongate beach ridges subparallel to present coastline; occurs in coastal & adjacent inland areas of S.E. S.A., extending into adjacent areas of western Vic.	Locally unconformable over Palaeozoic basement rocks of Padthaway Ridge, Tml, TQv; disconformable over Tps, Qpl; interfingers with & locally conformable under Qcl; unconformable under Qca, Qdm, Qhe, Qhl, Qho; deposited in coastal beach & associated aeolian dune environments
Early to ?Late Pleistocene	(Qpu)	Well cemented pale grey fine-grained dolomitic algal boundstone with intraclasts of sandstone, calcarenite, dolomite; in places capped by sheet calcrete	27 m mainly in range 4-15 m	Forms flat coastal plain in S.E. S.A.	Disconformable over Qpl; interfingers with basal Qpb, & Qfr of Marmon Jabuk Scarp; disconformable under Qca, Qdm, Qly, Qdl, Qho; deposited in marginal-marine, lacustro-lagoonal environments
Early Pleistocene to Holocene	Bakara Calcrete, Ripon Calcrete & other calcrete deposits (Qca)	Strongly cemented pale grey massive sheet calcrete, calcrete rubble, friable white & cream rhizolithic & nodular calcrete; includes intraclasts of various lithologies set in calcrete matrix	2 m mainly <1 m	Locally forms massive resistant sheets, particularly in S.A.; elsewhere, calcrete rubble underlies much of aeolian Mallee landscape in W., & calcrete glaebules & rhizoliths occur in many soil profiles throughout basin	Unconformable to disconformable over Tml, Tps, Tpn; Disconformable over Qpc, Qpb, locally over older components of Qly; mainly associated with Qdw, & also with Qdp, Qfr; deposited in pedogenic, groundwater, lacustrine, & biogenic environments of diagenesis
Early Pleistocene to Holocene	Pooraka Formation & other colluvial & residual deposits (Qfr)	Unconsolidated red-brown, poorly sorted clayey sand, gravel, conglomerate, breccia; local calcrete intercalations & cappings; in places cemented by ferruginised, silicified matrix	30 m mainly in range 1-5 m	Forms extensive coalesced low-angle fans, high-angle talus cones & scree slopes; colluvial aprons occur throughout flanking highlands; particularly well developed in N.W., where extensive coalesced fans of Pooraka Formation offlap Mount Lofty & Flinders Ranges	Unconformable over pre-Cainozoic basement rocks, Ta, Tml, Tps, Tpn, Qpc, Qca; interfingers with Qdp, Qdw, TQs; disconformable to unconformable under Qa; deposited in colluvial sheet-wash, alluvial-fan, & residual lag environments

TABLE 11. (page 4 of 4)

CAINOZOIC

LATE TERTIARY — QUATERNARY

Age	*Unit*	*Lithology*	*Thickness*	*Distribution & Landform*	*Remarks*
Early Pleistocene	Coomandook Formation (Qpl)	Partly lithified grey, cream fossiliferous medium-grained quartz sand, calcareous sand, calcarenite, sandy clay; characteristically contains lithic clasts & skeletal debris derived from older limestone	75 m mainly much thinner	Occurs beneath coastal area of S.E. S.A.; entirely concealed	Disconformable to unconformable over Tml, Toe; disconformable under Qpb, Qcl, Qpu, Qdm, Qfr; deposited in shallow-marine environment
Late Pliocene to Early Pleistocene	Blanchetown Clay & associated Bungunnia Limestone (Qpc)	Poorly consolidated to friable, well laminated greenish grey, red-brown clay; locally mottled, silty, sandy, calcareous, & gypsiferous; includes minor intercalated quartz sand, ostracod sand; contains calcareous, gypsiferous, siliceous nodules; overlain in W. by well cemented flaggy dolomitic limestone consisting of laminated micrite, oomicrite, oolitic & pisolitic calcarenite, oolitic algal biolithite	20 m mainly few metres only	Mainly concealed; locally exposed in river cliffs & lake margins; erosional remnants underlie aeolian sediments of much of central-west of basin	Unconformable over TQs, Tps, Tpn, Tml; interfingers with & overlain by TQs; disconformable to unconformable under Ql, Qly, Qa, Qdw, Qdp, Qca, Qfr; deposited in mainly freshwater lacustrine environment; locally saline lacustrine & fluvial environments



(a) (b)

Fig. 47. (a) *Nothofagidites emarcidus* **and (b)** *Nothofagidites asperus* **(Southern Beech). Nothofagus pollen is indicative of evergreen temperate rainforest and is characteristically present in many continental sediments of Eocene to Miocene age in southeastern Australia; supplied by E.M. Truswell – photographed with scanning electron microscope at magnification of x1000.**

CAINOZOIC STRATIGRAPHY – LOWER TO MID-TERTIARY SEQUENCE

Lower to Mid-Tertiary sediments of the Renmark Group and its constituent formations (Warina Sand and Olney Formation) form the basal depositional sequence of the Cainozoic stratigraphic succession of the Murray Basin. The Group underlies almost the entire basin. It consists mainly of fluvio-lacustrine deposits, but in western areas, particularly towards the top, it includes intercalated marine sediments. In the southwest of the basin, these have been differentiated as the separate, but poorly defined, Buccleuch beds.

Unit: Renmark Group (including Renmark beds in S.A.)
Age: ?Paleocene to Middle Miocene
Map symbol: Ter
Component formations: Warina Sand (Tew), including Lower Renmark beds (S.A.) – ?Paleocene to Eocene in age;
Olney Formation (Teo), including Upper Renmark beds (S.A.) – Eocene to Middle Miocene in age; and
Moorlands Lignite Member of the Olney Formation (Table 12)
Synonyms: Knight Sands and Clays, Knight Group, Knight Beds, Renmark Beds

Lithology. Light-brown or grey quartz sand predominates at the base of the Renmark Group (see 'Warina Sand' – Tew), whereas increasingly argillaceous and carbonaceous sediment predominates up-sequence (see 'Olney Formation' – Teo). Beneath tributary highland valleys and adjacent areas of the Riverine Plain, the Renmark Group contains a significant content of fine to medium-grained gravel. In the Moorlands area (PINNAROO), a series of coal seams is known as the Moorlands Lignite Member (Table 12) of the Olney Formation of the Renmark Group (formerly upper Renmark beds S.A.). Similar unnamed coal seams of Eocene to Middle Miocene age are widespread within the Olney Formation elsewhere in the basin.

Distribution, thickness and geometry. The Renmark Group is the most extensive and thickest of the units of the Murray Basin, forming a virtually continuous subsurface blanket of sediment over 300 000 km^2 (Fig. 48). Structure contours on the lower surface of the Renmark Group (see Plate 3 – base Cainozoic) indicate that the basal components infill depressions in the buried pre-Cainozoic topography, and onlap basement ridges concealed beneath the basin as well as the structural elements flanking the basin.

Isopachs of the Renmark Group (Plate 5) indicate that local thickening and thinning of the Group reflect variations in the configuration of the underlying basement topography, as well as Cainozoic re-activation of basement fractures. In particular, the Group was deposited in two major depocentres each

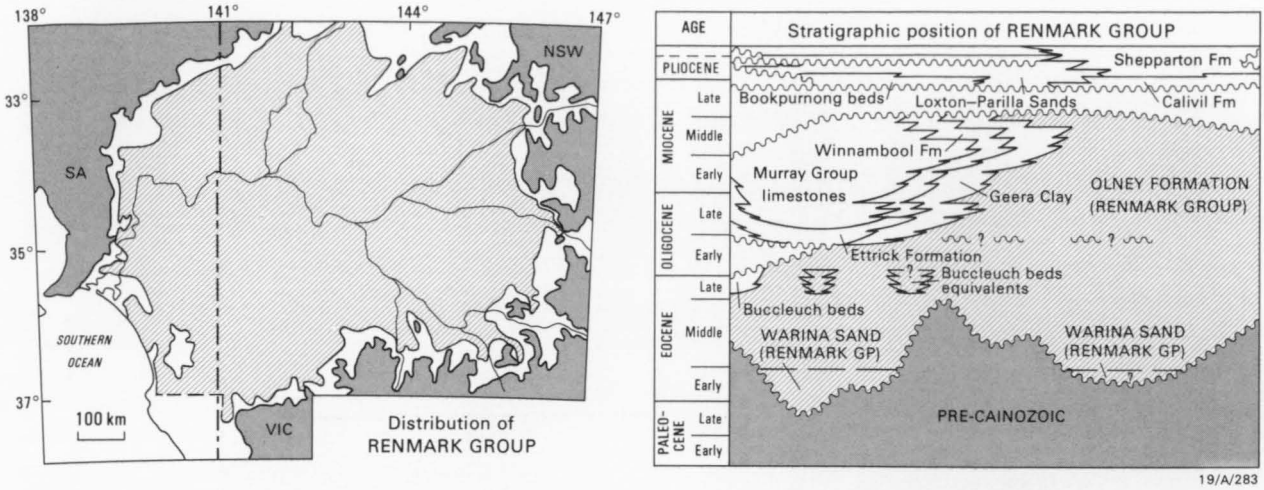


Fig. 48. Distribution and stratigraphic position of Renmark Group.

with several hundred metres of sediment; one of these underlies the central-western Murray Basin and the other underlies the Riverine Plain. Pockets of relatively thick sediment are preserved in areas underlain by pre-Cainozoic infrabasins, which have undergone minor differential subsidence during the Cainozoic, whereas thinner sequences are present over up-faulted but concealed basement blocks. Over the Renmark Trough and Paringa Embayment, for example, in excess of 300 m of Renmark Group has been encountered in boreholes, such as A.A.O. Sunset No.1 (Fig. 36; Derrington & Anderson, 1970). Beneath the western Riverine Plain, the Renmark Group is 281 m thick in Woodside Bundy No.1 (Fig. 30; Shiels, 1962; Brown & Stephenson, 1986), but locally thins to less than 50 m beneath the western margin of the Riverine Plain, before thickening again towards the central-western depocentre of the basin. This thinning beneath the western extremities of the Riverine Plain partly reflects onlap of the Renmark Group over concealed basement rises such as the Iona Ridge of the Ivanhoe Block (Fig. 4), and partly reflects the stratigraphic replacement of younger components of the Renmark Group by laterally equivalent units such as the Geera Clay. Beneath most northern, southern and eastern areas of the basin, the Renmark Group is generally less than 150 m thick, and commonly thins to a few tens of metres over basement rises and towards the basin margins. In contrast, the contiguous, correlative succession of the 'Knight Group' in the Gambier Embayment of the Otway Basin to the south is 704 m thick in O.D.N.L. Mt. Salt No.1 (Oil Development N.L., 1962; Cundhill & Stach, 1963, 1965; fig. 3–2 of Ludbrook, 1971).

Variations in the elevation of the upper surface of the Renmark Group (Plate 6) are due partly to the influence of local syn-depositional and post-depositional differential subsidence of underlying basement troughs and rises. In addition, the Group occurs at relatively shallow depths and at a stratigraphically higher level in eastern and northern areas of the basin, in comparison with western areas (Fig. 48).

Outcrop. The Renmark Group is entirely concealed within the Murray Basin, but minor occurrences of equivalent sediments are exposed to the south of the basin in the Glenelg River valley in western Victoria (see enclosed 1:1 000 000 geological map), and in a quarry located on the Padthaway Ridge in southeast South Australia (Allen's Quarry – see 'Type section'; Fig. 51). In addition, minor outcrops of coarse-grained residual and valley-fill sediments of undifferentiated Tertiary age within the highland valleys of northern Victoria probably include coarse-grained correlatives of the Renmark Group (see 'Undifferentiated residual and valley fill sediments – Ta'; Kenley, 1976c, 1988c).

Palaeontology and age evidence. The Renmark Group contains abundant carbonized plant remains, and the finer-grained components have well-preserved palynological assemblages of spores and pollen (Harris, 1971). Sediments in western areas, particularly towards the top of the Renmark Group, locally preserve impoverished larger foraminifera and rare planktonic foraminifera (e.g. Ludbrook, 1961a, 1964; Lawrence, 1966; Ludbrook & Lindsay, 1969), and dinoflagellate cysts (Harris, 1970, 1973; Paten & Price, 1970; Macphail & Truswell, 1988, 1989; Lindsay & Barnett, 1989; see Fig. 55).

The Group ranges in age mainly from Eocene to Mid-Miocene, but the oldest preserved components

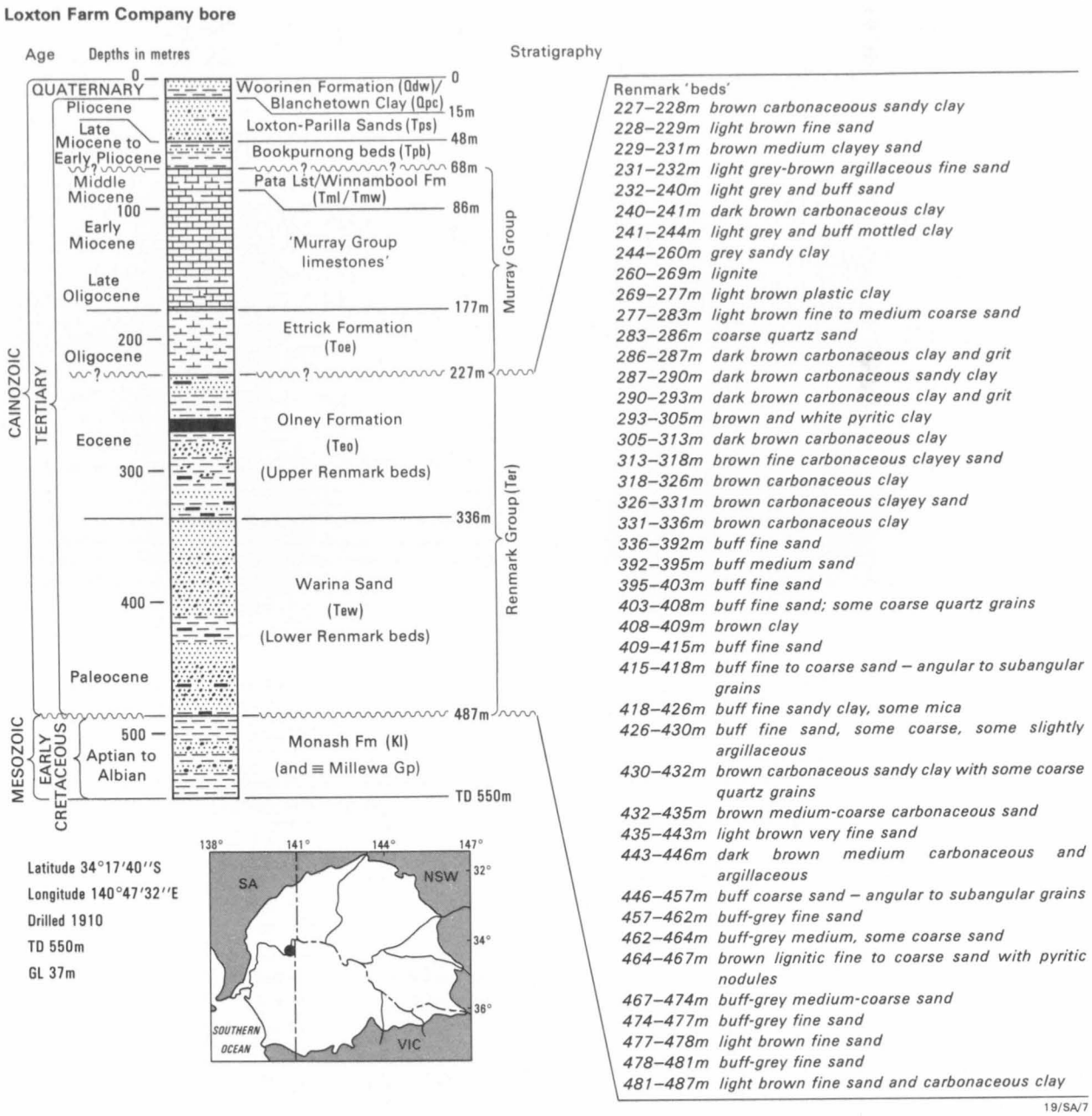


Fig. 49. Lithology log of Loxton Farm Company Bore (based on fig. 1 of Ludbrook, 1961a). Harris (1966) nominated the interval between 227 and 487 m as type section of 'Renmark Beds' — now Renmark Group. Thornton (1974) subdivided 'Renmark Beds' into 'Upper Renmark Beds' (now Olney Formation) and 'Lower Renmark Beds' (now Warina Sand).

are possibly Paleocene (Harris, 1970, 1973) and appear to be restricted to the deepest, central-western parts of the basin (see 'Warina Sand'). Elsewhere, the basal sediments have been found to contain mainly Middle to Upper Eocene microfloral assemblages (e.g. Harris, 1964, 1985; Harris & Morgan, 1976; Macphail, 1987, 1988a,b; Truswell, 1987), whereas beneath the northern and eastern margins of the basin, where the Group onlaps flanking basement elements, the basal components are commonly of Oligocene or Miocene age (e.g. Truswell & others, 1985). The upper surface of the Group is diachronous and in southwestern areas the uppermost sediments are mainly Late Eocene–?Early Oligocene in age (Thornton, 1974), whereas in eastern and northern areas of the basin, the truncated uppermost sediments are Early or Middle Miocene in age (see 'Olney Formation').

Interpretation of environment of deposition. The presence of abundant carbonaceous material, and diagnostic palynological assemblages, in combination with a general lack of marine fossils in eastern areas

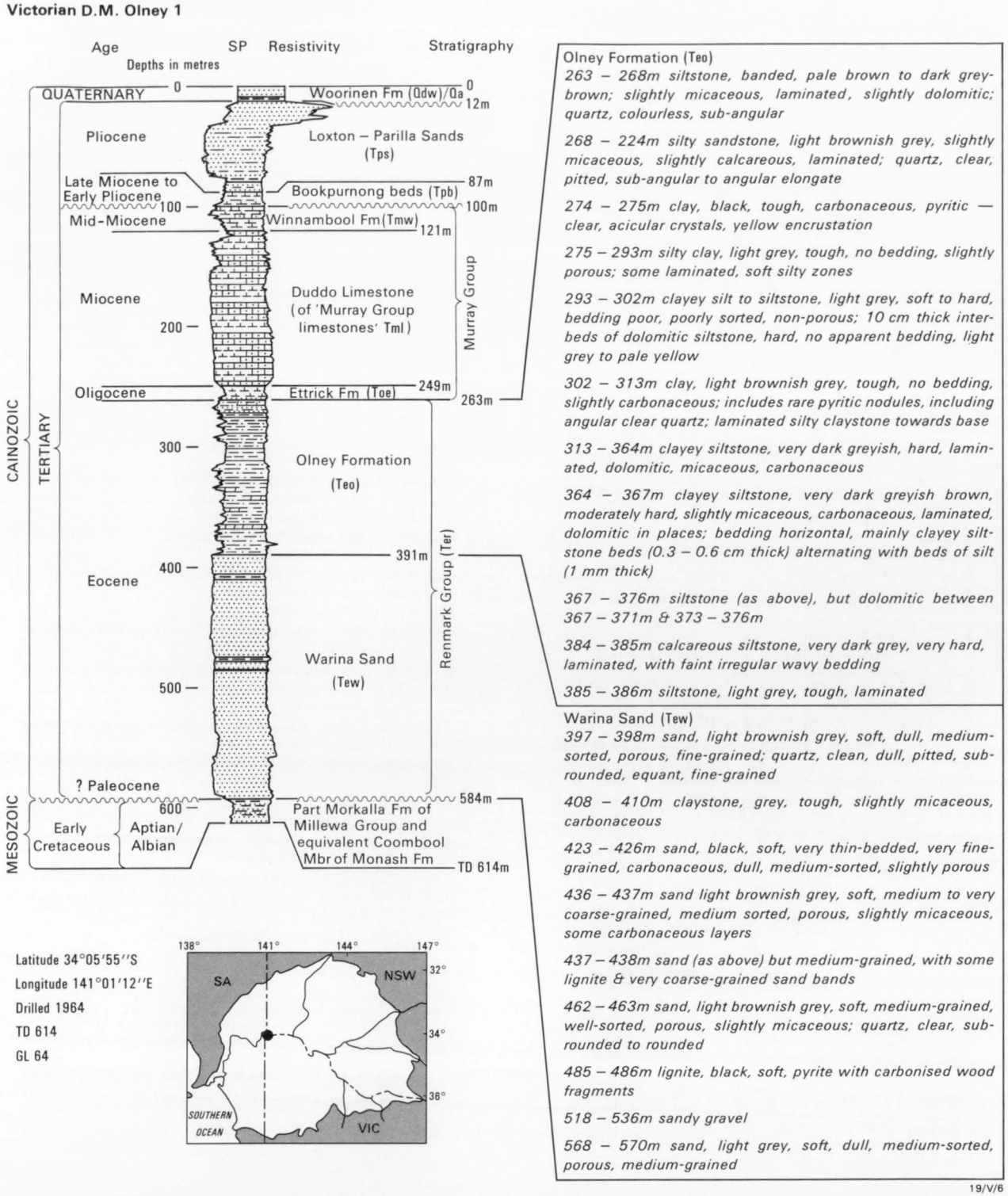


Fig. 50. Lithology log of Vic. D.M. Olney No. 1; containing type section of Renmark Group, Olney Formation and Warina Sand (modified after Lawrence, 1975).

indicates that most of the Renmark Group was deposited in fluvio-lacustrine environments (see 'Warina Sand' and 'Olney Formation' for discussion). The local presence of marine fossils (mainly dinoflagellates), and the association of intercalated coal-bearing and marine sediments within parts of the Group in some western areas, suggests local deposition in marine, paralic and deltaic environments, particularly in the Late Eocene–Early Oligocene (see Fig. 55 for known approximate extent of marine influence). The marine sediments are lithologically distinct in the southwest, where they include carbonates, and are differentiated as the Buccleuch beds.

Stratigraphic nomenclature. The stratigraphic name 'Renmark Group' was defined by Lawrence (1975) in

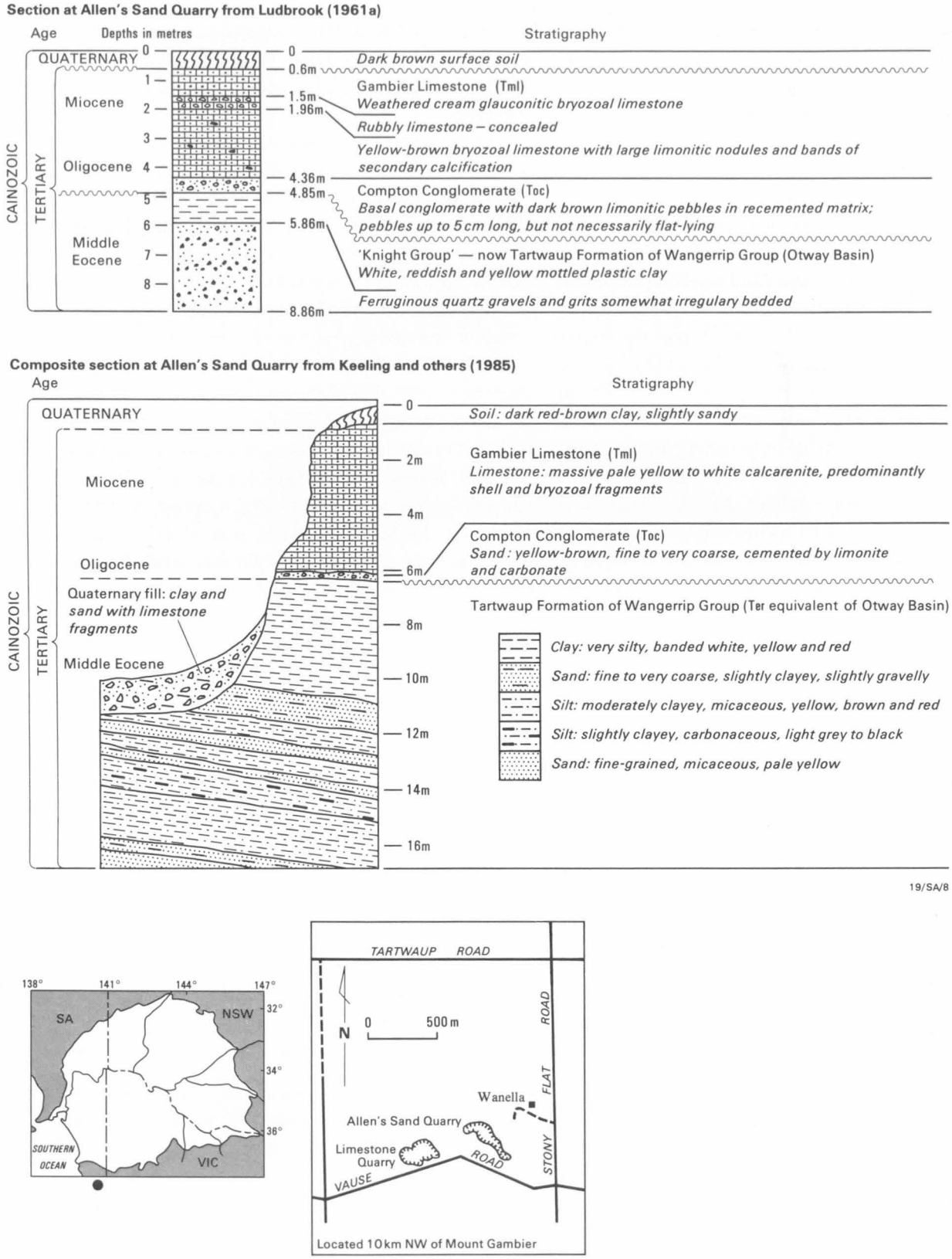


Fig. 51. Type sections of 'Knight Beds' and Compton Conglomerate in Allen's Quarry (after Ludbrook, 1961a; Keeling & others, 1985). This site is the only known surface exposure in South Australia of sediments equivalent to the Renmark Group in the deeper parts of the Murray Basin and Gambier Embayment. The section has therefore been listed as a geological monument (Mooney, 1977). Prior to the definition of the 'Renmark Beds' by Harris (1966), the name 'Knight Group/Beds' was applied to the equivalent non-marine Early to Mid-Cainozoic sediments of the Murray Basin (e.g. Ludbrook, 1961a). N.B. 'Knight Group' was originally named after Knight's Quarry, now Allen's Quarry.

Victoria, and is a modification of the name 'Renmark Beds' as defined by Harris (1966) in South Australia (Fig. 45). The Group was named after the town of Renmark (northeast RENMARK).

In South Australia, Thornton (1974) recognised two units within the Renmark beds of Harris (1966) and named these, respectively, the 'Lower and Upper Renmark Beds'. Lawrence (1972, 1975) recognised a similar subdivision in Victoria and defined the Renmark Group and two component formations. These consist of the basal predominantly sandy unit (Warina Sand – Tew) and the upper, more widely distributed and lithologically variable Olney Formation (Teo; Lawrence, 1975). Kellett (1988, 1989) has identified at least three further, as yet unnamed, subdivisions of the Olney Formation in the POONCARIE–IVANHOE–BALRANALD area of the central-northern Murray Basin (see 'Olney Formation'). The nomenclature of Lawrence (1975) is widely used in Victorian and New South Wales literature and has been adopted in this Bulletin when referring to the basin as a whole. The original terminology of Harris (1966) and Thornton (1974) has been retained only in reference to occurrences of the unit in South Australia. We suggest that the nomenclature of the Renmark Group be adopted throughout the basin.

Synonyms. The Renmark Group of Lawrence (1975) is synonymous with the 'Renmark Beds' of Harris (1966) and is partly equivalent to the 'Knight sands and clays' of Sprigg (1952a), the 'Knight Group' of Sprigg & Boutakoff (1953) and Ludbrook (1957, 1961a). The Renmark Group is also equivalent to the 'Knight Beds' of Firman (1973), and partly equivalent to the 'Knight Formation' of Harris (1966). Prior to publication of the definition of 'Renmark Beds' by Harris (1966), the names 'Knight Group' or 'Knight Beds' were applied to the non-marine, Early to Mid-Cainozoic sediments of both the Murray Basin and adjacent Gambier Embayment of the Otway Basin to the south. Currently, however, the name 'Knight Group'/'Knight Formation' is restricted to correlative, but lithologically distinct and substantially thicker, equivalent formations in the Gambier Embayment (Wopfner & Douglas, 1971).

Type sections. Harris (1966) nominated the 260 m thick interval, between 227 m and 487 m in Company No.1 bore, as the type section of the Renmark beds in South Australia (Fig. 49). The bore was drilled as a petroleum exploration well in 1910 by the Loxton Farm Company (Ludbrook, 1961a; Thornton, 1974) and is located over the Renmark Trough, southeast of Loxton (RENMARK). Material from the type section is held at the South Australian Department of Mines and Energy core and drill-cutting store in Adelaide.

Lawrence (1975) nominated the 321 m thick interval between 263 m and 584 m in Vic. D.M. Olney No.1 stratigraphic bore as the type section of the Renmark Group in Victoria (Fig. 50; see descriptions of type sections of Warina Sand and Olney Formation).

Sediments of the Renmark Group are not exposed at the surface, but the former type section of the unit (Fig. 51; now the type section of the Tartwaup Formation of the equivalent Knight Group sediments of the Gambier Embayment) is exposed in Allen's Quarry (formerly Knight's Quarry) on Section 718, Hundred of Blanche [13 km northwest of Mount Gambier (PENOLA); Sprigg, 1952a; Ludbrook, 1961a, 1969a]. The section is the only known surface exposure of sediments equivalent to those of the deeper parts of the Murray Basin and Gambier Embayment in South Australia and has therefore been listed as a geological monument (Mooney, 1977).

Stratigraphic relationships. The Renmark Group forms the basal unit of the Murray Basin and hence unconformably overlies virtually all of the pre-Cainozoic tectono-stratigraphic elements constituting the structural framework of the Murray Basin. The stratigraphic relationships of the component units of the Group are described under 'Warina Sand' and 'Olney Formation'. Regional correlatives of the Renmark Group in other basins of southeastern Australia are given in Wopfner & Douglas (1971), Lindsay (1985a), and Harris (1985).

Economic geology and aquifer characteristics. See 'Warina Sand', 'Olney Formation', 'Groundwater' and 'Coal'.

Remarks. The basal Renmark Group is lithologically similar to sands of the Jerilderie Formation from the Oaklands infrabasin beneath the southeast Murray Basin. These sedimentary rocks were originally thought to be Tertiary in age, but were subsequently found to be of Mid-Triassic age by Morgan (1977a). Elsewhere beneath the Riverine Plain, it is therefore conceivable that some of the undated basal sand sequences of the Renmark Group may prove to be Triassic in age. In the central-western depocentre of the basin, the Warina Sand locally overlies dated Lower Cretaceous sediments and no misidentification can arise.

Data sources. See 'Warina Sand' and 'Olney Formation'.

Unit: Warina Sand of the Renmark Group, including Lower Renmark beds (S.A.)
Age: ?Paleocene to Eocene
Map symbol: Tew (also part of undifferentiated Ter)
Synonyms: Lower Knight Group, Lower Knight Beds, Lower Renmark Beds, Warina Formation

Lithology. The dominant lithology of the Warina Sand (formerly 'Lower Renmark Beds' in S.A.) is pale-grey to pale-brown, poorly consolidated, medium to coarse-grained quartz sand and sandstone. The formation also includes thin beds of intercalated fine sand, silt, clay and minor pebble conglomerate. At the base of the formation, the sand is poorly sorted and gritty (Ludbrook, 1961a), whereas in the central parts of the basin moderately to well-sorted orthoquartzitic and protoquartzitic sands have been encountered in bores, such as Vic. D.M. Olney No.1 (Fig. 50; Lawrence, 1972, 1975). The sand is mainly weakly consolidated, loose to friable, but is in places weakly lithified by siliceous cement, intergranular clay, carbonaceous material, and/or quartz–pyrite aggregates. In some bores, these aggregates have been oxidised to form a ferruginous encrusting cement.

Abundant muscovite is present within sand encountered beneath northwestern areas, perhaps reflecting the metamorphic provenance of material derived from the adjacent Broken Hill and Willyama basement blocks. Elsewhere, the quartz sand is only slightly micaceous, with flecks of muscovite, scattered carbonized plant fragments and pyritized wood debris. Individual sand grains are pitted, spherical, subrounded to rounded, consisting mainly of clear or milky quartz grains with minor chert clasts (Thornton, 1974; Lawrence, 1966, 1975). Several suites of accessory minerals have been reported, but these vary from borehole to borehole. Lawrence (1975), for example, noted the presence of tourmaline, zircon, rutile, and psilomelane in Vic. D.M. Olney No.1 (Fig. 50). The relatively low clay content and paucity of unstable feldspar and mafic grains suggest that the sand of the formation is both texturally and chemically mature. Many of the sands are probably polycyclic in origin, and, in comparison with those of the Olney Formation, they are relatively clean, porous and permeable. In vertical profiles, grain size fluctuates irregularly from coarse to fine sand, and intercalated fine clastics are thin (in most deep bores in the central-west), irregularly spaced and relatively rare.

The thin interbeds of fine-grained sand, silt and clay are commonly dark in colour, highly carbonaceous to lignitic, with abundant pyritized wood debris. In A.A.O. Morkalla No.1 (Fig. 39), an anomalous lithology of 10 m of hard, micritic, dark-brown to grey dolomitic limestone was intersected within the Warina Sand (Lower Knight Group of Derrington & Anderson, 1970; Thornton, 1974). Similar dolomitic sediment has also been recorded within the Warina Sand in several other boreholes in central and western areas. The depositional setting of the dolomite is not known, but lacustrine or diagenetic origins related to precipitation from groundwater are a possibility. Detailed descriptions of borehole sections are recorded in a number of petroleum exploration well completion reports (see Table 45).

Distribution, thickness and geometry. The Warina Sand has been encountered in only a few boreholes, and hence the detailed distribution of the unit is poorly known (boreholes in N.S.W. and Victoria are listed in Brown & Stephenson, 1986; those in South Australia are in Thornton, 1974). The available data do, however, indicate that the unit is absent over areas of shallow basement beneath the basin, and is absent towards the basin margins. Thick deposits are confined to deeper central-western parts of the basin. Basal sand deposits, in deeper parts of the basin beneath the western Riverine Plain, were tentatively assigned to the Warina Sand by Woolley & Williams (1978), but thick extensive sections similar to those beneath central-western areas have not yet been encountered. The formation appears to be entirely absent beneath the Riverine Plain east of Hay (Woolley & Williams, 1978), and has not been identified within the Renmark Group in the southeast of the basin (Tickell & Humphrys, 1979, 1980). Several thin sand sequences at the base of the Renmark Group in eastern and southern areas of the basin have previously been logged as Warina Sand (e.g. in Lawrence, 1975), but the age of most of these is unknown. It seems likely that many of these sands could be basal coarse-grained Olney Formation rather than Warina Sand, and we suggest that only the thicker sediments of ?Paleocene–Eocene age, encountered in the deeper parts of the basin, should be assigned to the Warina Sand.

The Warina Sand is thickest in the central-western part of the basin (Thornton, 1974) where 231 m of section was encountered by Beach Monash No.1 (Walter, 1965; Fig. 38), 212 m by Beach Berri North No.1 (Laws & Heisler, 1967; Fig. 38), 184 m by A.O.C. North Renmark No.1 (Grasso, 1963; Fig. 35), 168 m in A.A.O. Morkalla No.1 (Derrington & Anderson, 1970; Fig. 39), and 186 m was intersected

by A.A.O. Sunset No.1 (Derrington & Anderson, 1970; Fig. 36). The unit thins rapidly to the south where 63 m was encountered by M.B.O.S. Pinnaroo No.1 (O'Driscoll, 1960), and to the north where 143 m was intersected by A.O.G. Lake Victoria No.1 (Grasso, 1964; Fig. 39), 86 m by A.O.G. Wentworth No.1 (Rose, 1962a; Fig. 39), and 42 m by A.O.G. Tararra No.1 (Boyd & Heisler, 1967; Fig. 28). Farther east, the presence of the Warina Sand is less certain beneath the western Riverine Plain. Woodside Bundy No.1 (Shiels, 1962; Fig. 30) encountered 111 m of section (including 30 m of clay), which Woolley & Williams (1978) interpreted as Warina Sand. Generally, however, the unit is only a few tens of metres thick towards its eastern limits of distribution and only 32 m of possible Warina Sand were encountered by NSW Oil & Gas Hay No.1 (Haskell, 1970b; Woolley & Williams, 1978). The thickness of the unit is thus highly variable and regional variations in the geometry of the formation reflect variations in the buried pre-Cainozoic topography.

Outcrop. The Warina Sand is the basal unit of the Murray Basin succession, and is entirely concealed.

Internal geometry. The sections encountered by petroleum exploration wells indicate that the formation consists mainly of stacked, multi-storied, massive sand bodies, with a few irregularly spaced thin interbeds of fine clastics. Gamma and Self Potential Resistivity logs running through the basal contact of the unit are irregularly spiked, due to the influence of underlying pre-Cainozoic weathering profiles, and the presence of chemically immature clasts in the basal few metres of the formation. Up-sequence, many gamma logs are characterised by a rapid initial coarsening-upward signature (e.g. gamma log profiles on Figs 36, 38, 39, 40), followed by a uniformly low gamma count and relatively smooth profile through the main body of the formation. This reflects the massive, relatively clean, character of the sand. Irregularly spaced low wave-length, high amplitude spikes are due to the presence of thin carbonaceous or micaceous interbeds. Towards the top of the unit, gamma log profiles indicate increased preservation of truncated sets of upward-fining sand – silt – clay cycles.

Palaeontology. The Warina Sand contains scattered carbonized wood and plant debris as well as laminae and thin interbeds of lignitic clay, but micro-floral assemblages are not well-preserved because of the generally coarse and permeable nature of the sandy lithologies. Most of the sparse fossil material is present in the less-abundant finer-grained sediment and consists primarily of fossil wood, twigs, leaves and spore assemblages. Paten & Price (1970) noted that the basal part of the unit includes proteaceous elements with characteristically few *Nothofagidites*, but has swarms of *Deflandra*-like dinoflagellates, whereas upper parts of the unit are characterised by an extremely abundant and diverse proteaceous and *Nothofagidites* content. Other palynological descriptions are recorded in reports by Harris (1970, 1973).

Age evidence. Few palynological age determinations have been obtained from the Warina Sand, and the precise age limits of the formation are therefore poorly known. Paleocene sediments were first recognised in the Warina Sand by Harris (1970) who correlated microfloral assemblages at the base of the Warina Sand (Lower Renmark beds) in the Loxton Farm Company bore with the Middle Paleocene *Gambierina edwardsii* zonule of Harris (1971). Near the base of the unit in A.A.O. Morkalla No.1, Harris (1973) subsequently obtained non-marine dinoflagellate cysts, consisting mainly of *S. gravattensis* and *M. pyramidalis* of Middle to Late Paleocene age. These are thought to be representative of the oldest phase of Cainozoic sedimentation in the Murray Basin. No sedimentary rocks of equivalent age have as yet been identified beneath eastern areas of the Murray Basin. Thornton (1974) noted that the boundary between the Warina Sand (Lower Renmark beds in S.A.) and the overlying Olney Formation (Upper Renmark beds) lies near the top of the *Proteacidites pachypolus* zonule of Middle Eocene age. Paten & Price (1970) had earlier obtained an Eocene age from palynological material from A.A.O. Morkalla No.1, Sunset No.1 and Nadda No.1. Woolley & Williams (1978) assigned a Middle to Late Eocene age to the formation beneath the western Riverine Plain on the basis of examination of palynological assemblages by Martin (1977), although as noted above, some of the samples yielding Late Eocene ages may be from basal sands of the overlying Olney Formation. A Lower *Nothofagidites asperus* pre-*Triorites magnificus* zone of Middle Eocene age was identified in basal sands in Woodside Bundy No.1 by Martin (1977). No sediments of Paleocene age have as yet been located beneath the Riverine Plain.

Characteristics. The Warina Sand forms locally thick, homogeneous sand bodies, which are confined in distribution to the deeper basal sections of the Murray Basin. The upper boundary of the formation with the lithologically similar basal Olney Formation is in places difficult to determine, but is generally marked by a greatly increased up-sequence content of interbedded fine-grained, carbonaceous clastics.

The base of the unit is commonly underlain by several metres of white to grey kaolinitic clay, which appears to be an Upper Cretaceous weathering profile developed over underlying pre-Cainozoic sedimentary and basement rocks.

Interpretation of environment of deposition. Thick Warina Sand was deposited mainly in a slowly subsiding depression in the pre-Cainozoic landscape of central-western areas of the basin. The formation was possibly also deposited in similar depressions beneath parts of the Riverine Plain. Interbedded siltstone, clay and carbonaceous sediment are mostly thin and poorly represented in comparison with the overlying Olney Formation. It seems possible that marine influences extended into the Murray Basin during Paleocene–Eocene periods of marine highstand, but so far as is known the Warina Sand has no foraminifera or other indications of marine influence. It contains freshwater dinoflagellates (Harris, 1973), and is characterised by the presence of plant debris and pyritized wood fragments. These indicators suggest that the sand was deposited by large, high-discharge rivers which were both laterally and vertically aggrading to produce a series of stacked sand bodies. The irregular grain-size profiles in combination with the paucity of thin, marginal floodplain deposits indicate a possible braided or anastomosed stream pattern characterised by rapid switching between multiple channels. The high sand content indicates transportation of bed-load in a system with an abundant supply of coarse-grained clastics. The textural and chemical maturity of the relatively clean sand of the formation suggests a polycyclic origin. The increasing content of silt, clay, and lignite towards the top of the formation, in combination with the presence of profiles in which grain-size diminishes up-sequence, may indicate a change in fluvial style from braided/anastomosed to confined and possibly meandering channel sands, increasingly flanked by fine-grained lacustrine and floodplain deposits. This up-sequence change may have resulted from decreased palaeogradients accompanying infill of the depressions in the pre-Cainozoic landscape, and/or changes in relative sea-level.

The influx and preservation of coarse sediment in the Early Tertiary records the initiation of deposition and preservation of the Murray Basin succession, accompanying uplift of the southeast highlands after the Late Mesozoic–Early Tertiary break-up of the southern margins of the Australian continent. In addition, the development of this basal succession of the Murray Basin was coincident with an apparent eustatic rise in relative sea-level, and the consequent rise in base-level of sedimentation may have contributed to preservation of sediment within topographic depressions. The interpreted palaeoclimate is thought to have been both humid and warm, as indicated by the presence of abundant wet rainforest assemblages in Paleocene/Eocene sedimentary rocks in adjacent basins and highland areas (e.g. Kemp, 1978a; Truswell & Harris, 1982; McGowran, 1978a).

Stratigraphic nomenclature. The formation is the lowermost unit of the Renmark Group and was named by Lawrence (1975) after the Parish of Warina, 90 km west of Mildura.

Synonyms. The Warina Sand is synonymous with the Lower Knight Group (e.g. Derrington & Anderson, 1970), and Lower Renmark beds of Thornton (1974). The names Lower Knight beds and Warina Formation have also appeared in the literature.

Type section. The type section of the Warina Sand is 193 m thick and is located between 391 m and 584 m in Vic. D.M. Olney No.1 bore (Fig. 50; Lawrence, 1975). It consists of light-grey to light brown-grey, loose to friable, medium to coarse, moderately to well-sorted, slightly micaceous orthoquartzitic sand. Material from the type section is housed at the core and cutting store of the Victorian Department of Industry, Technology and Resources, Melbourne. Thornton (1974) assigned a 151 m thick interval between 336 m and 487 m within the type section of the Renmark beds of Harris (1966), in Loxton Farm Company No.1 bore to the 'Lower Renmark Beds' (Fig. 49).

Stratigraphic relationships. The Warina Sand is the basal unit of the Renmark Group. In places it unconformably overlies a pre-Cainozoic basement. Locally, a low-angle unconformity or disconformity separates the formation from underlying weathered Lower Cretaceous and Lower Permian sedimentary rocks, preserved within concealed infrabasins beneath the western Murray Basin. The unit is thought to be conformably overlain by the Olney Formation, but the relationship between the two units is poorly understood – and, because the coarse-grained clastics of the Warina Sand do not yield palynological assemblages, the boundary remains undated. It is thought to be gradational, although alternatively, the rapid up-sequence change from a sand-dominated sequence to a silt–sand–clay–coal sequence may reflect the presence of a hiatus between the two units, and future investigations may prove the relationship to be a disconformable one. Paten & Price (1970) examined correlations between

palynological zonules in the A.A.O. Nadda No.1, Morkalla No.1, and Sunset No.1 petroleum exploration wells, noting that the lower part of the *Triorites magnificus* zonule of Harris (1970) is absent from the basal component of the Olney Formation in Nadda No.1, but is present in Sunset No.1 and Morkalla No.1. They concluded that the base of the Olney Formation is partly diachronous and suggested the presence of a hiatus corresponding with a change in lithofacies from Warina Sand ('Lower Renmark Beds') to Olney Formation ('Upper Renmark Beds'). They also noted that this conclusion is supported by log correlations between the three wells. In contrast, Lawrence (1975) noted that there are problems in identifying the boundary between the two formations because of the similar lithologies in the uppermost Warina Sand and lowermost Olney Formation.

Aquifer characteristics. The Warina Sand is characterised by clean sand, high porosity and good permeability and is a high-yielding semi-confined aquifer (Lower Renmark aquifer subsystem of Reed, 1980; see 'Groundwater'). It forms part of the Renmark Group aquifer system.

Remarks. The Warina Sand (Victoria and N.S.W.) clearly correlates with the Lower Renmark beds of Thornton (1974) in South Australia, and it is recommended that the name 'Warina Sand of the Renmark Group' be adopted throughout the basin.

Data sources. Stratigraphic descriptions of the Warina Sand (and 'Lower Renmark Beds' in S.A.) are to be found in Lawrence (1966, 1975), Derrington & Anderson (1970), Harris (1970, 1971, 1973), Paten & Price (1970), Lawrence & Goldberry (1973), Thornton (1974), Martin (1977), Woolley & Williams (1978), and Reed (1980).

Unit: Olney Formation of the Renmark Group, including Upper Renmark beds (S.A.)
Age: Eocene to Middle Miocene
Map symbol: Teo
Member: Moorlands Lignite Member (Table 12)
Synonyms: Lower Knight Group, Lower Knight Beds, Lower Renmark Beds, Lower Renmark Group

Lithology. The Olney Formation (formerly 'Upper Renmark Beds' in S.A.) is a lithologically variable unit consisting of intercalated, laterally discontinuous, thin beds of unconsolidated to poorly consolidated, coarse to fine terrigenous clastics. The dominant lithologies are carbonaceous silt, siltstone, sand, clay, and claystone, with common interbeds of lignitic brown coal and peat. The sand is dark brown, grey, black, carbonaceous, pyritic, and locally micaceous. Laminae of carbonized plant fragments and abundant scattered lignitic wood debris are common. Beneath the tributary valleys of the Victorian Highlands and adjacent areas of the Riverine Plain, the Olney Formation contains a significant proportion of fine to medium-grained gravel (e.g. Bartley & Reid, 1987; Brinkley & others, 1988).

The sand grains are predominantly quartz and chert, with angular ferruginous and pyritic clasts, as well as varying proportions of lithic clasts. Many quartz grains are iron-stained and coated by sesquioxides. Sorting of the sand grains is highly variable, and textures range from coarse, poorly-sorted, gritty sand to fine, moderately to well-sorted, finely laminated, silty sand. Fresh cuttings samples are commonly weakly lithified by a ferruginous intergranular clay matrix, and in places by quartz–pyrite aggregates, or carbonaceous material. The sand is also weakly cemented by siliceous, carbonaceous, dolomitic or calcareous cements. Intergranular matrices range from black and grey carbonaceous silt and clay to white kaolinitic clay. In Woodside Balranald No.1 (Fig. 52), the basal 32 m (from 290 m to 322 m), consists of anomalous light-brown dolomitic sandstone (of uncertain age, but assumed to be part of the Olney Formation; Ludbrook, 1962a). The sand content of the formation can be as high as 80–100% in some boreholes in tributary highland valleys. Similarly high sand contents locally occur in the distributary fans, which developed where major palaeo-rivers exited from the highlands. Within the basin, however, the sand content diminishes rapidly to less than 50% within a short distance of the basin margins. Throughout much of the basin, silt is the dominant lithology of the Olney Formation, and the channel sand content is highly variable. The Formation appears to be relatively sandy, however, beneath the area drained by the lower Darling River, possibly reflecting the greater availability of quartz-rich sand derived from the Broken Hill basement block to the northwest, as well as sand re-cycled from the Darling Basin to the north. Farther east, boreholes located beneath the western margins of the Riverine Plain locally intercept thick channel sands, but mostly encounter thick silty floodplain and lacustrine sediments.

Sandy silt and silty clay components commonly form alternating laminae. They contain angular quartz sand grains, carbonaceous debris, pyrite and micaceous material, and some are weakly lithified. The clay is often cohesive and puggy when wet, but friable when dry. The silt and clay vary in colour,

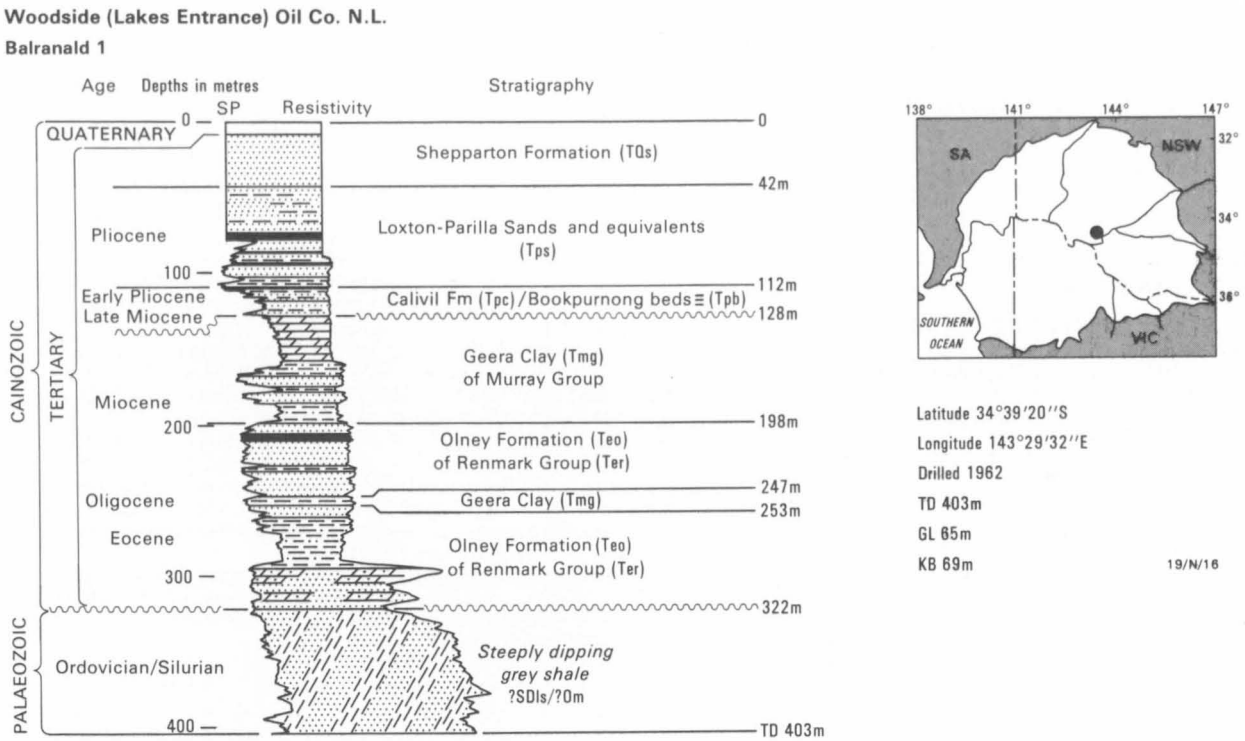


Fig. 52. Lithology log of Woodside (Lakes Entrance) Balranald No. 1 (modified after Benbow, 1962; Ludbrook, 1962a; Martin, 1977; Woolley & Williams, 1978).

from brown to dark brown, black or blue-black, but towards the basin margins and in basal sequences the clay is commonly pale-grey to white kaolin. This basal white clay is probably derived from underlying Upper Cretaceous weathering surfaces, which separate the Olney Formation from the underlying pre-Cainozoic basement. Diagenetic calcareous and dolomitic cemented siltstones have been especially noted in the upper part of the Olney Formation (Lawrence, 1966).

The peat, peaty clay, and lignitic brown coal contain sporadic disseminated pyrite cubes and nodules, but few leaf fragments. The peats are generally of low rank and are currently undergoing decay, so that when cored the odour of marsh gas has been reported (Yoo, 1981a, 1982). At Moorlands in South Australia, where the coal interbeds have been found to be sufficiently thick, they have been differentiated as the Moorlands Lignite Member (see Table 12).

Other units within the Olney formation have not generally been recognised, although in north-central areas Kellett (1989) sub-divided the formation into three units of hydrogeological significance, in which the middle unit is consistently finer-grained than either the upper or lower ones.

Distribution, thickness and geometry. The Olney Formation is the thickest and most widely distributed formation in the Murray Basin (Fig. 48). It is only absent over a few concealed basement ridges, and beneath the fringes of the basin where younger basinal sediments onlap rising bedrock topography – a zone which is several tens of kilometres wide. At the basin margins, concealed tongues of Olney Formation also form part of the sediment infill of tributary valleys extending back into the adjacent highland zone.

Isopachs (Plate 5) indicate considerable variation in the thickness of the formation, partly because the unit unconformably onlaps an irregular pre-Cainozoic surface, and partly because the upper surface of the formation is diachronous. The two major depocentres (see 'Renmark Group' and 'Warina Sand') each contain up to 200 m of sediment. The depocentre located in the central-west of the basin is separated from the one beneath the Riverine Plain by an arcuate zone of concealed northwesterly and northeasterly trending basement ridges underlying the western margins of the Plain. In addition, beneath the central-western Riverine Plain the Olney Formation is laterally replaced by the Geera Clay, and consequently thins to less than 50 m and locally to only a few metres. In the west, where the Olney Formation is replaced up-sequence by marine sediments of the Murray Group, deposition of the formation ceased in the late

TABLE 12. EOCENE MOORLANDS LIGNITE MEMBER OF THE OLNEY FORMATION

Unit: Moorlands Lignite Member of Olney Formation

Age: Eocene

Map symbol: included in Teo

Synonyms: Moorlands Coal Measures, Moorlands Coal Measures of Knight Beds, Moorlands Lignite Member of Renmark Beds, Brown-Coal Bearing Beds of Moorlands, Brown-Coal Sequence at Moorlands

Lithology. Moorlands Lignite Member is poorly defined; 'Brown-Coal Sequence' of McGarry (1953, p.84) adopted as type description. Lithologies vary up-sequence from: (a) basal conglomerate, in places coarse-grained, elsewhere only sand or clay; (b) grey clay, usually with coal fragments; (c) chocolate-brown lignite, finely interbedded lignite, clay; irregular fracture; small bands water-worn quartz pebbles; plant remains abundant — leaves, resin, woody matter; pyrite, marcasite, in bands and disseminated — locally replace woody material; (d) carbonaceous clay, carbonaceous sandy clay; and (e) uppermost lithology — grey carbonaceous sand with fine-grained, water-worn quartz, very little carbonaceous material.

Distribution and thickness. Small area near settlement of Moorlands, S.A. (see Fig. 171). McGarry (1953) mapped five small lignite bearing basins, although Rogers (1980a) mentions six. Thickness varies greatly, up to maximum of 20 m. Basal conglomeratic sand (a) has patchy distribution with maximum thickness of 1 m. Grey clay (b) up to 6 m. Maximum known thickness of lignitic bed (c) less than 17 m. Units (d) and (e) are thin, not extensive (McGarry, 1953).

Palaeontology and age evidence. Abundant plant material, including leaves, woody parts, resin. Crespin (1953) identified no datable fossils, but assigned Late Eocene age, on basis of foraminiferal material from surrounding Renmark Group; this age corresponds with later palaeontological work by Ludbrook (1957, 1961a).

Characteristics. Differentiated from surrounding Olney Formation by lithology in area of occurrence; Olney Formation has numerous lignite beds elsewhere in Murray Basin — Moorlands Lignite Member distinguished from these on geographic and stratigraphic position.

Environment of deposition. Deposited in fresh-water lakes and swamps, formed in local depressions on Kanmantoo Group basement (McGarry, 1953; Rogers, 1980a). Basal conglomerate rests directly upon this basement in places. (McGarry, 1953);

Stratigraphic nomenclature and type section. Named after township of Moorlands, S.A. Mawson & Chapman (1922) described 'Tertiary Brown-Coal Bearing Beds of Moorlands'; informally described by McGarry (1953) as "brown-coal sequence at Moorlands"; Ludbrook (1961a) referred to 'Moorlands Coal Measures' of Knight Beds; 'Moorlands Lignite Member of the Renmark Beds' proposed by Harris (1966). In this Bulletin, unit referred to as Moorlands Lignite Member of Olney Formation. No formal type section defined for Moorlands Lignite Member, although name in common use; description of McGarry (1953) forms standard section.

Stratigraphic relationships. Part of Olney Formation (formerly 'Upper Renmark beds' in S.A. — equivalent to lower part of Olney Formation in N.S.W. and Victoria). In places, unconformable over Kanmantoo Metamorphics, which form basement in Moorlands area (Rogers, 1980a); elsewhere lies conformably within paralic/fluvio-lacustrine sediments of Olney Formation.

Hydrogeology and economic geology. Holds saline groundwater (part of Renmark Group aquifer system). Apparently no local recharge in Moorlands area; original connate waters possibly still present (O'Driscoll, 1960).

Moorlands coalfield pattern-drilled by S.A. Department of Mines; proven reserves 31.75 million tonnes of lignite (Moorlands Coal Measures), in six small basins. Average thickness of seams 6.5 m; overburden to coal ratio about 5:1 (Rogers, 1980a). Because of water saturation, coal disintegrates on exposure to air. On 12% moisture basis, average composition of coal is: fixed carbon 28.5%, volatile matter 39.5%, sulphur 4.2%, ash 20%, with average calorific value of 18.6 megajoules per kg (Johns, 1975). Tested as potential source of montan wax, but found to be of poor quality (Nixon, 1972, 1973).

Remarks. Moorlands coalfield one of several small subeconomic brown coal deposits within Renmark Group/Olney Formation; Moorlands Lignite has historically been accorded status of distinct stratigraphic unit, but is no more geologically deserving of this than Anna and Bower Coalfields or other similar deposits elsewhere within Olney Formation.

Data sources. Mawson & Chapman (1922), Crespin (1953), McGarry (1953), Ludbrook (1957, 1961a), O'Driscoll (1960), Harris (1966), Nixon (1972, 1973), Johns (1975), Rogers (1980a), Brown & Stephenson (1986).

Early-Oligocene, whereas it continued in the east and north until the Mid-Miocene. Consequently, in eastern and northern areas, the Olney Formation occurs at relatively shallow depths in comparison with those in western areas. In A.O.C. North Renmark No.1 (Fig. 35), Eocene–Lower Oligocene components are 150 m thick and occur at a depth of 215 m, whereas beneath the Riverine Plain in the east, Eocene–Mid Miocene components in N.S.W. Oil & Gas Hay No.1 occur at a depth of 120 m and are 182 m thick. The thickest section recorded by Brown & Stephenson (1986) is 209 m of Eocene–Mid Miocene sediment, encountered at a depth of 84 m in N.S.W. Oil & Gas Booligal No.2.

Structure contours on the lower surface of the formation (Fig. 4; Plate 3 — base Cainozoic) indicate that the basal sediments of the Olney Formation overlie a topographically irregular surface. In contrast, structure contours on the top of the formation reflect the influences of post-depositional differential subsidence, as well as the diachronous nature of the upper surface (Plate 6).

Internal geometry. Gamma logs and Self Potential Resistivity logs are highly variable in character, and consist of irregular profiles with numerous high amplitude spikes. Irregularly spaced sets of upward increasing gamma count occur within these profiles. Each set is only a few metres thick and is either sharply truncated by a zone of low gamma response at the base of the overlying set, or alternatively merges into an overlying irregularly spiked profile. When examined in conjunction with lithology logs, the profiles are interpreted to indicate the presence of floodplain and lacustrine silts and clays with common carbonaceous clay and coal intercalations, and minor upward-fining sand to clay, fluvial channel sequences.

Outcrop. Within the Murray Basin, the Olney Formation is entirely concealed. Equivalent sediments are exposed in the Gambier Embayment of the adjacent Otway Basin and in highland valleys to the south (see 'Renmark Group' and 'Undifferentiated

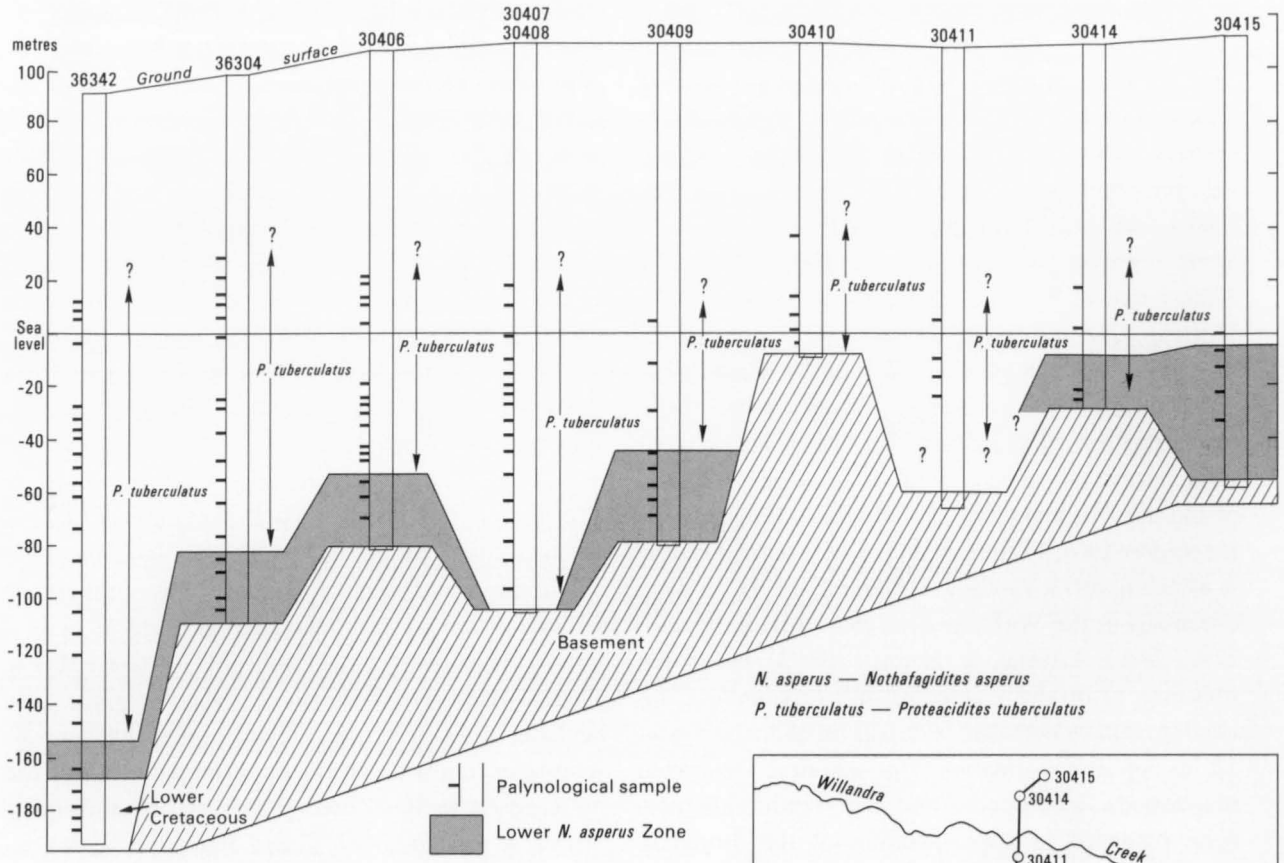
residual and valley fill sediments – Ta').

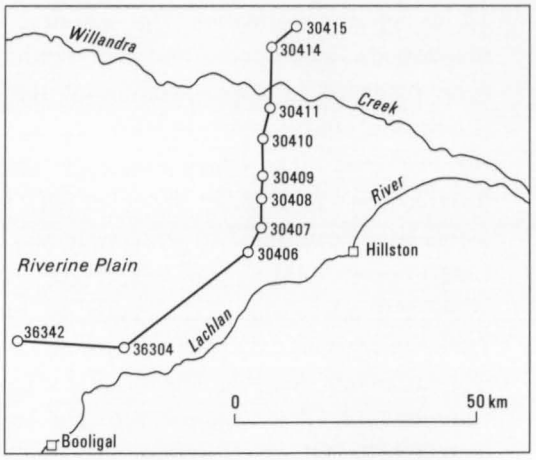
Palaeontology. The Olney Formation characteristically contains carbonized plant remains, including fossil logs, woody peat and leaf litter. The finer-grained components of the formation include well-preserved palynological assemblages of spores, pollen (see 'Age Evidence' below), and in western areas, dinoflagellate cysts (Harris, 1966, 1971, 1973, 1985; Paten & Price, 1970; Harris & Morgan, 1976; Martin, 1977, 1984a,b,c; Truswell & others, 1985; Truswell, 1987; Macphail, 1987, 1988a,b; Macphail & Truswell, 1988, 1989). Beneath western areas of the basin, the top of the Olney Formation locally contains poorly preserved larger foraminifera and rare planktonic foraminifera (Ludbrook, 1961a, 1964; Lawrence, 1966; Ludbrook & Lindsay, 1969; Lindsay & Bonnett, 1973; Lindsay & Barnett, 1989). In deep boreholes in the Waikerie area (SADME bores 2W, 27W, 28W), Lindsay & Bonnett (1973) noted the presence of bivalve fragments and foraminifera, including *Chiloguembelina cubensis* in the uppermost 12 m of the formation. In addition, restricted scaphopods, gastropods, and fish teeth have also been recorded in upper sections of the formation (Ludbrook, 1961a).

Age evidence. The Olney Formation ranges in age from Eocene to Middle Miocene. The basal sediments have been found to preserve mainly Middle or Late Eocene floral assemblages (Harris, 1966, 1985; additional references in Appendix 4), but beneath the basin margins, where the formation onlaps flanking basement elements, the basal components are commonly of Oligo-Miocene age (e.g. basal section in SADME Oakvale No.1 bore; Truswell & others, 1985). In a basal section of the Olney Formation ('Upper Knight Group') in A.A.O. Sunset No.1, Morkalla No.1 and Nadda No.1, Paten & Price (1970) identified specimens of *Triorites magnificus*, which they correlated with the late Middle Eocene to early Upper Eocene *Triporopollenites magnificus* zonule of Harris (1971). In basal sediments beneath northern areas of the basin, Macphail (1987, 1988a,b) and Truswell (1987) identified assemblages of Lower *Nothofagidites asperus* (Middle Eocene), through Lower *Proteacidites tuberculatus* (Early Oligocene) and Upper *Proteacidites tuberculatus* (Late Oligocene to Early Miocene) age. Beneath the southeast Riverine Plain, Harris & Morgan (1976) identified palynological assemblages ranging from Middle Eocene Lower *Nothofagidites asperus* to Oligocene *Proteacidites tuberculatus* in basal Tertiary sections in boreholes overlying the Oaklands infrabasin. In a series of palynological studies undertaken by Martin (1977, 1984a,b,c) and Truswell (1987), basal components of the formation beneath the Riverine Plain were found to range mainly from equivalents of the Lower and Middle *Nothofagidites asperus* Zone of Stover & Partridge (1973) and Partridge (1976) – Middle to Late Eocene in age, but probably mainly Late Eocene – to the *Proteacidites tuberculatus* Zone of Oligo-Miocene age. The Late Eocene Upper *Nothofagidites asperus* Zone of Stover & Partridge (1973), for example, has been identified in N.S.W. Oil & Gas Hay 1 (Martin, 1977) and other boreholes beneath the western Riverine Plain (e.g. Truswell, 1987), but has not generally been identified in bores farther to the northeast examined by Martin (1984b,c), although it is possible that equivalent sediments are present, but lack diagnostic assemblages.

In the southwest of the basin, the uppermost sediments are of Late Eocene or Late Eocene–Early Oligocene age (Ludbrook, 1961a, Harris, 1966). However, beneath northern areas, and beneath the Riverine Plain, palynological assemblages indicate that the uppermost sediments can be assigned to the *Triporopollenites bellus* Zone of Stover & Partridge (1973) and Partridge (1976), indicating a Middle Miocene upper age, possibly extending into the earliest Late Miocene (Macphail, 1987, 1988a,b, Truswell, 1987). The presence of an erosional surface at the top of the Olney Formation is indicated by the absence of *Triporopollenites bellus* assemblages of Middle Miocene age from the top of the formation in many boreholes in eastern areas, where overlying Upper Miocene–Lower Pliocene sediments directly overlie the Olney Formation with *Proteacidites tuberculatus* assemblages of Lower Miocene age. The *Triporopollenites bellus* Zone is, for example, entirely absent in boreholes beneath the Lachlan area of the Riverine Plain (Martin, 1984c), but is present in many boreholes beneath the Murrumbidgee area (Martin, 1984b).

During the Eocene to Middle Miocene, deposition was probably intermittent and the assigned age range includes a number of periods of non-deposition. Stratal breaks are indicated by ferruginised surfaces, palaeosols and intraformational erosional or non-depositional surfaces within the formation. Variations in the thickness of components of the formation assigned to different palynological zones in different parts of the basin also reflect variations in depositional and erosional/preservational patterns. A prominent regional hiatus is thought to have occurred in the late Early Oligocene, accompanying a fall in sealevel (see 'Cainozoic Sedimentation Patterns'). In southern and western areas (mainly the





AGE	PALYNOLOGICAL ZONES GIPPSLAND BASIN (Stover and Partridge, 1973; Partridge, 1976)	MODIFIED ZONES EASTERN MURRAY BASIN (Martin, 1984a)
MIOCENE Middle	*T. bellus* Zone	*T. bellus* Zone
MIOCENE Early	Upper	*P. tuberculatus* Zone
OLIGOCENE Late	*P. tuberculatus* Zone Middle	
OLIGOCENE Early	Lower	
EOCENE Late	Upper	Lower *N. asperus* Zone
EOCENE	*N. asperus* Zone Lower	

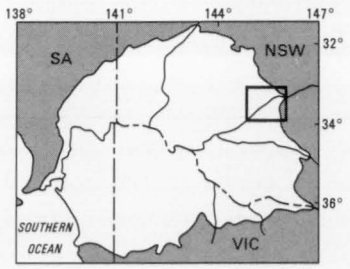


Fig. 53. Tertiary palynological zones in correlated borehole sections in eastern Murray Basin (after Martin, 1984c). Samples above *P.tuberculatus* Zone are largely barren, but are thought to be mainly Pliocene in age.

South Australian sector of the basin), deposition of the Olney Formation (formerly Upper Renmark beds) continued into the Oligocene, but locally ceased (or was not preserved) before deposition of the overlying Compton Conglomerate, Ettrick formation, Winnambool Formation or Geera Clay of the marine Murray Group. To the east and north, however, accumulation of lithologically similar diachronous equivalents continued until the Middle Miocene, and was followed by a major basin-wide early Late Miocene non-depositional hiatus. To the east and north, the postulated early Oligocene hiatus therefore occurs within the upper Olney Formation rather than at the contact between the formation and the overlying Murray Group. Evidence of erosional breaks between Eocene–Lower Oligocene and Oligo-Miocene sediments of the Olney Formation beneath parts of the Riverine Plain is only tentative, and comes from correlated borehole sections which appear to show intraformational erosion. For example, Figure 53 (based on several figures in Martin, 1984c) shows sediments assigned to the Oligo-Miocene *Proteacidites tuberculatus* Zone entrenched up to 60 m within sediment assigned to the Middle *Nothofagidites asperus* Zone. Major thickness variations of sections assigned to subdivisions of the *Proteacidites tuberculatus* Zone also occur from borehole to borehole.

In north-central areas of the Murray Basin, the uppermost unit of the three-fold subdivision of the Olney Formation of Kellett (1989) lies within the Mid to Late Miocene *Triporopollenites bellus* Zone; the middle unit straddles the Upper *Proteacidites tuberculatus* (Late Oligocene to Early Miocene) and basal *T. bellus* Zones; whereas the lower unit preserves pollen assemblages of the Lower to Middle *Nothofagidites asperus* Zones (Middle to Late Eocene) and extends into the Lower *P. tuberculatus* (Early Oligocene) Zone (Truswell, 1987; Macphail & Truswell, 1989).

In summary, the Oligocene–Middle Miocene components of the Olney Formation are often lithologically indistinguishable from the Eocene–Lower Oligocene components, in the absence of palynology. Therefore, in accordance with the lithostratigraphic emphasis given to the definition of stratigraphic units, and in the absence, thus far, of regionally identifiable marker horizons, the variously dated components of the Olney Formation are at present regarded as parts of a single lithostratigraphic unit (Brown, 1985; Brown & Stephenson, 1986).

Characteristics. The principal characteristic of the Olney Formation is the abundant carbonaceous debris in silt, sand, and clay. The formation is also characterised by rapid vertical and lateral lithologic variability. Marine fossils are generally absent, except within uppermost components of the formation in western and southwestern areas, where the Olney Formation is conformably overlain by, or interfingers with, marine sediments of the Eocene Buccleuch beds and Oligo-Miocene Murray Group. Palaeontological evidence indicates that minor equivalents of the Buccleuch beds and Murray Group are locally intercalated within the Olney Formation, but these cannot yet be differentiated on lithology alone and are therefore included within the Olney Formation in this Bulletin (see also 'Remarks' and 'Buccleuch beds').

The top of the Olney Formation can generally be determined by the first appearance of abundant carbonaceous material. In eastern areas of the basin, the overlying Calivil Formation consists of quartz sand within a white kaolinitic clay matrix, and lacks carbonaceous material. However, in many boreholes beneath the Riverine Plain, the Calivil Formation consists mainly of clay, and cannot readily be distinguished from the Olney Formation. Similarly, in some boreholes beneath the tributary valleys at the basin margins in the northern Victorian highlands, the Olney and Calivil Formation each contain coarse-grained sands and conglomerates within a kaolinitic matrix, and are difficult to differentiate (e.g. Tickell & Humphrys, 1979, 1980, 1987). In some bores near the basin margins, the Calivil Formation is absent, and the Olney Formation is directly overlain by the lithologically similar Shepparton Formation. Carbonaceous material is, however, generally lacking in the Shepparton Formation.

Interpretation of environment of deposition. The presence of lignitic brown coal and peat, abundance of carbonaceous detritus, palynological evidence, and general lack of marine fossils, indicate that the Olney Formation was deposited in predominantly non-marine environments. Interpretations of lithology and geophysical log profiles, in combination with the predominance of silt-sized sediment, suggest that most of the Olney Formation was deposited in extensive floodplain and lacustrine environments, whereas sand deposits were largely confined to meandering channel environments. Fossil logs and lignitic debris are common within the fluvial channel sands. The peaty coals are thought to have been deposited in extensive swamp and marsh environments with fringing forests. Some of the coal-forming swamps were paralic (Harris, 1985). In SADME Oakvale No.1

bore in the northwest of the Murray Basin, palynological evidence from the Geera Clay suggests that in the Oligocene the regional vegetation was dominated by evergreen rainforest, and local open-water and swamp conditions are indicated by the presence of abundant grass and sedge pollen, freshwater algae, freshwater dinoflagellates, and swamp vegetation (Truswell & others, 1985).

In western areas, the Olney Formation includes sediments with marginal-marine to marine dinoflagellates, and locally with impoverished foraminiferal faunas. These sediments are probably transitional between the entirely non-marine sediments to the east and the marine formations to the west, and probably include minor intercalated components deposited in coastal plain, shifting deltaic, paralic to shallow-marine environments. As discussed previously (see 'Remarks', 'Renmark Group' and 'Buccleuch beds'), Late Eocene–Early Oligocene marine equivalents of the Buccleuch beds has been found within the Olney Formation in several bores in western areas. The approximate distribution of these sediments is shown on Figure 55. In some bores towards the northern and eastern limits of the marine Murray Group, thin sand and clay occur between underlying marginal-marine Geera Clay and the overlying Loxton–Parilla Sands. Macphail (1988b) dated these as Middle Miocene (*Triporopollenites bellus* Zone), and suggested that they represent tidal channel infill or tidal sand bar deposits at the top of the Geera Clay. They could also be considered to be marginal-marine components of the Olney Formation which regressed to the southwest, over the top of the Geera Clay, during a fall in relative sealevel in the Middle Miocene (see 'Cainozoic Sedimentation Patterns').

Stratigraphic nomenclature. The formation constitutes the uppermost unit of the Renmark Group and was named by Lawrence (1975) after the Parish of Olney, 100 km west of Mildura.

Synonyms. The Olney Formation of Lawrence (1975) is partly equivalent to the 'Renmark Beds' of Harris (1966), and is partly synonymous with the 'Upper Renmark Beds' of Thornton (1974). It is recommended that the synonyms be abandoned, and that the name 'Olney Formation' be adopted throughout the basin. In Victoria and New South Wales, the names Olney Formation and Renmark Group are frequently used interchangeably.

Type section. Lawrence (1975) nominated a 128 m thick interval between 263 m and 391 m in the Vic. D.M. Olney No.1 bore as the type section of the Olney Formation (Fig. 50). Core from the type section is available for inspection at the core and drill cutting store of the Victorian Department of Industry Technology and Resources, Melbourne. Thornton (1974) assigned a 109 m thick interval between 227 and 336 m within the type section of the 'Renmark Beds' (Loxton Farm Company bore; Fig. 49; Harris, 1966) to the synonymous Upper Renmark beds.

Stratigraphic relationships. At the western margin of the Murray Basin, the Olney Formation unconformably overlies and onlaps Proterozoic to Early Palaeozoic components of the Adelaide Fold Belt, Kanmantoo Fold Belt and Padthaway Ridge. In SADME Oakvale No.1 bore (see Fig. 77), for example, Upper Oligocene sediments of the unit unconformably overlie Adelaidean sediments at a depth of 154 m (Forbes, 1983; Lindsay, 1983a; Truswell & others, 1985). Farther east, the formation unconformably overlies Cambrian to Carboniferous components of the Lachlan Fold Belt, and in the north unconformably onlaps Devonian to Carboniferous sediments of the Darling Basin. A low-angle unconformity or disconformity separates the unit from residual remnants of Lower Cretaceous and Lower Permian sedimentary rocks, locally preserved in underlying fault-bounded troughs. Beneath the eastern margin of the basin, the formation also disconformably overlies remnant patches of Upper Permian and Middle Triassic sedimentary rocks, preserved within the underlying Oaklands Basin and adjacent concealed depressions. In the absence of underlying Warina Sand, the base of the formation is often characterised by a white kaolinitic clay – a weathering surface, which developed over most pre-Cainozoic sedimentary and basement rock surfaces, beneath the Murray Basin, in the Upper Cretaceous.

Within the deeper and more central parts of the basin, the Olney Formation overlies the Warina Sand with apparent conformity, although the exact relationship between the two formations is not known, and the contact has not been dated (see 'Warina Sand'). Beneath the southwest of the basin, Eocene components of the Olney Formation are conformably overlain by, and interfinger with, marine sediments of the Buccleuch beds. In some southwestern areas, Eocene components of the Olney Formation are disconformably overlain by Oligocene Compton Conglomerate and Ettrick Formation, and Oligo-Miocene limestone formations of the Murray Group (Gambier Limestone, Morgan Limestone, Mannum Formation and Duddo Limestone; Ludbrook, 1961a; Lawrence, 1966). In A.A.O. Morkalla No.1, Sunset No.1 and Nadda No.1, Der-

rington & Anderson (1970) suggested that an unconformity separates the upper Renmark Group from overlying Oligo-Miocene sediments of the Murray Group. Lindsay & Bonnett (1973) have suggested that in boreholes in the Waikerie area (RENMARK), the relationship between the Renmark Group/'Buccleuch beds equivalents' and the overlying Murray Group is a conformable one. Elsewhere, however, it may be an unconformable one (see 'Remarks').

Towards the northern and eastern limits of distribution of the marine Murray Group, Oligocene–Middle Miocene components of the Olney Formation are conformably overlain by, and interfinger with, onlapping transgressive components of the Ettrick Formation, the Geera Clay, and less commonly the Winnambool Formation. Abele (1970), for example, identified Janjukian foraminiferal assemblages within both the top of the Olney Formation and the base of the overlying Ettrick Formation. In addition, Archer (1974) could find no significant break between the two formations. Towards the top of the Olney Formation, slightly farther to the north and east, truncated Middle Miocene components interfinger with, and locally conformably overlie, regressive components of the Geera Clay, so that the Olney Formation locally envelops the Geera Clay (Fig. 48).

In the highland valleys of northern Victoria, the Calivil Formation is unconformably entrenched within the Renmark Group to depths of up to 60 m (Macumber, 1978a,b). In northern regions of the basin and beneath the Riverine Plain, the Olney Formation appears to be disconformably overlain by the Calivil Formation, and in some areas towards the basin margins the formation is also disconformably onlapped by Pliocene to Quaternary sediments of the Shepparton Formation. The formation is also locally disconformably overlain by Upper Miocene–Lower Pliocene sediments of the Bookpurnong beds and undifferentiated Loxton–Parilla Sands.

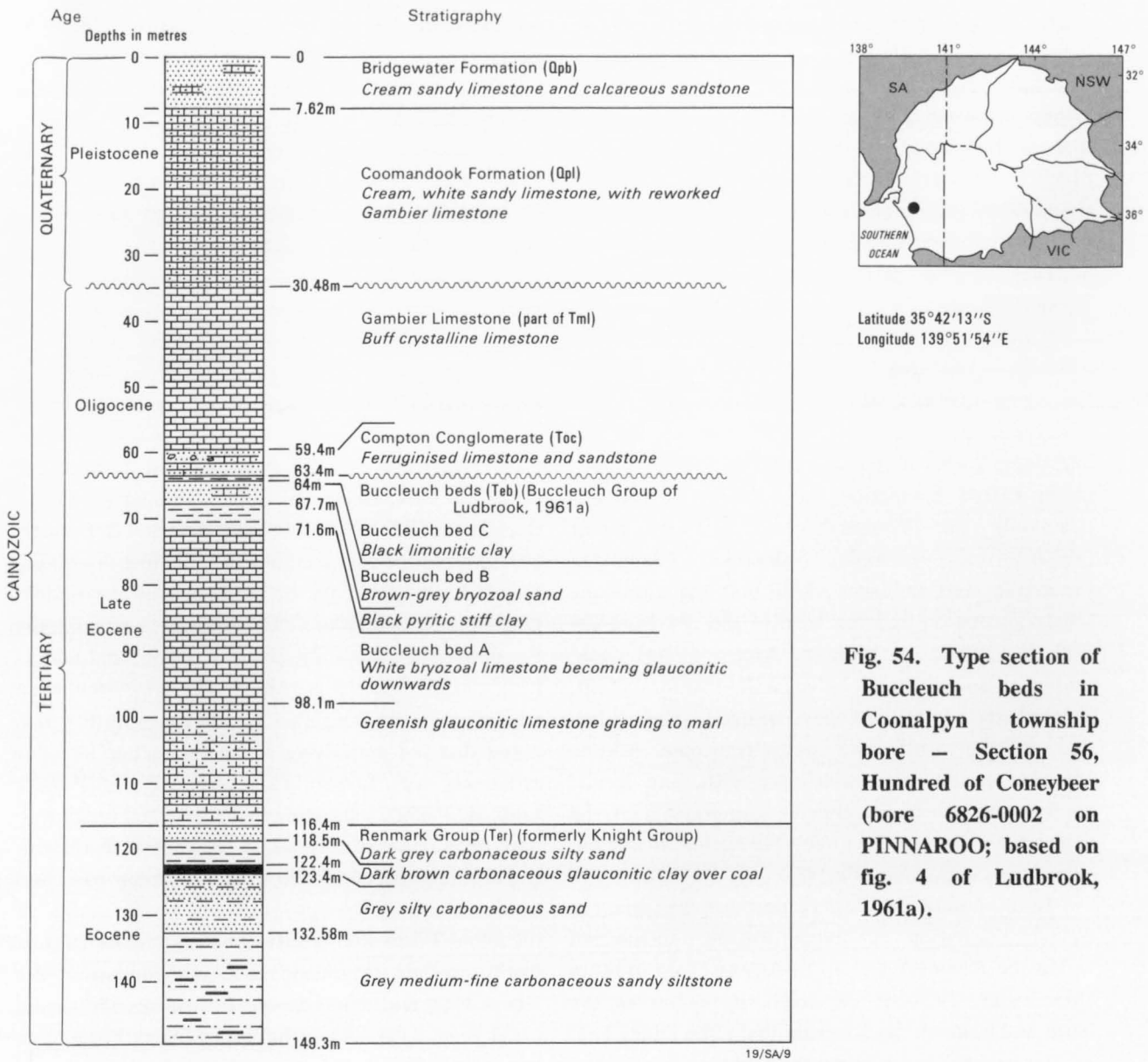
Correlative units. To the south of the Murray Basin, the Olney Formation can be correlated with contiguous equivalent, non-marine, Early to Mid-Tertiary sediments of the Gambier Embayment of the Otway Basin (Dartmoor Formation, Tartwaup Formation of the Knight Group; of Sprigg & Boutakoff, 1953, *in* Ludbrook, 1971). These have also been referred to as the 'Knight Formation' of the 'Wangerrip Group' by (Harris, 1966) and Ludbrook (1967c).

Economic geology and aquifer characteristics. The Olney Formation contains a number of poorly known but extensive deposits of Eocene to Middle Miocene peaty, lignitic brown coal. These include the Sedan deposits, and subeconomic Moorlands, Anna and Bower coalfields in South Australia. At Moorlands, these sediments are locally differentiated as the Moorlands Lignite Member (Table 12). Extensive deposits also occur beneath the Echuca and Kerang regions in Victoria (see 'Coal').

The unit forms part of the Renmark Group aquifer system (see Fig. 172 and 'Groundwater'), and underlies almost the entire Murray Basin.

Remarks. The disconformity between the Olney Formation and the Murray Group in southwestern areas can possibly be correlated with a major late Early Oligocene eustatic event of Vail & Mitchum (1979), as calibrated by Loutit & Kennett (1981). In deep bores in the Waikerie area, Lindsay & Bonnett (1973) recorded the presence of a distinct disconformity between the base of sediments of the middle Oligocene Ettrick Formation (Planktonic Foraminiferal Zone P.21; Lindsay, 1985a) and underlying marine sediments, which they suggested were equivalent to the Buccleuch beds. However, they also noted that the underlying marine sequence includes sediments of Lower Oligocene age (?P19/20; Lindsay, 1985a), suggesting that the stratal break may have been of short duration in the deeper tectonically subsiding parts of the basin. Farther east and north, where Oligocene–Miocene components of the Olney Formation interfinger with and are conformably overlain by transgressive components of the Geera Clay and Winnambool Formation, the stratal break may occur within the upper Olney Formation, but has not yet been recognised. Still farther east and north, palynological evidence of possible erosional breaks are recorded, where Oligocene to Middle Miocene components of the Olney Formation are locally entrenched within older Eocene components of the formation (Fig. 53; see 'Age Evidence' above). In most areas, however, the early Oligocene break is not readily detectable on lithology logs within the Olney Formation. The extent and duration of all suspected stratal breaks within the Olney Formation is uncertain and require further investigation. Therefore, as noted above, the Oligocene to Middle Miocene and Eocene components are considered to be part of a single relatively thin, lithologically distinct formation, within which stratal breaks are known to occur.

In this Bulletin, marine sediments of both Eocene–Oligocene and Oligocene–Miocene ages, which are present towards the upper contacts of the Olney Formation in western to central areas, are presumed to represent marine intercalations within



Latitude 35°42′13″S
Longitude 139°51′54″E

Fig. 54. Type section of Buccleuch beds in Coonalpyn township bore – Section 56, Hundred of Coneybeer (bore 6826-0002 on PINNAROO; based on fig. 4 of Ludbrook, 1961a).

the formation. These are viewed as being equivalent to, or transitional with, either the Eocene marine Buccleuch beds or the marine units of the Oligo-Miocene Murray Group, but may eventually prove to be separate and distinct formations. In the northwest of the basin, for example, a grey sand unit occurs between the Eocene Olney Formation and the Oligocene Ettrick Formation. Lindsay & Bonnett (1973) correlated this unit in CHOWILLA and part of RENMARK with the Buccleuch beds and – on the basis of foraminifera collected from the grey sand unit in two bores drilled near Waikerie – suggested that deposition of the Buccleuch beds continued into the Oligocene (see 'Buccleuch beds'). There are, however, two other possibilities: either that the grey sand unit is a transitional marine component of the mainly fluvial Olney Formation, or that the unit is a correlative of the Oligocene Compton Conglomerate – rather than the Buccleuch beds (S.R. Barnett, S.A.D.M.E., personal communication, 1984). A similar sand unit which occurs below the Geera Clay in bores in ANABRANCH, MENINDEE and OLARY (e.g. SADME Oakvale No.1; Truswell & others, 1985) is also tentatively included here in the Olney Formation.

Sediments with Upper Eocene assemblages, equivalent in age to those of the Buccleuch beds, have been identified in BMR/DWR (NSW) Woodlands-1 bore (on ANABRANCH) and Vic. D.M. Piangil West-1 (SWAN HILL) by Macphail (1988a,b) – these are lithologically similar to the Renmark Group but have sparse dinoflagellate assemblages and, although lacking other evidence of marine influence, may have been deposited in coastal

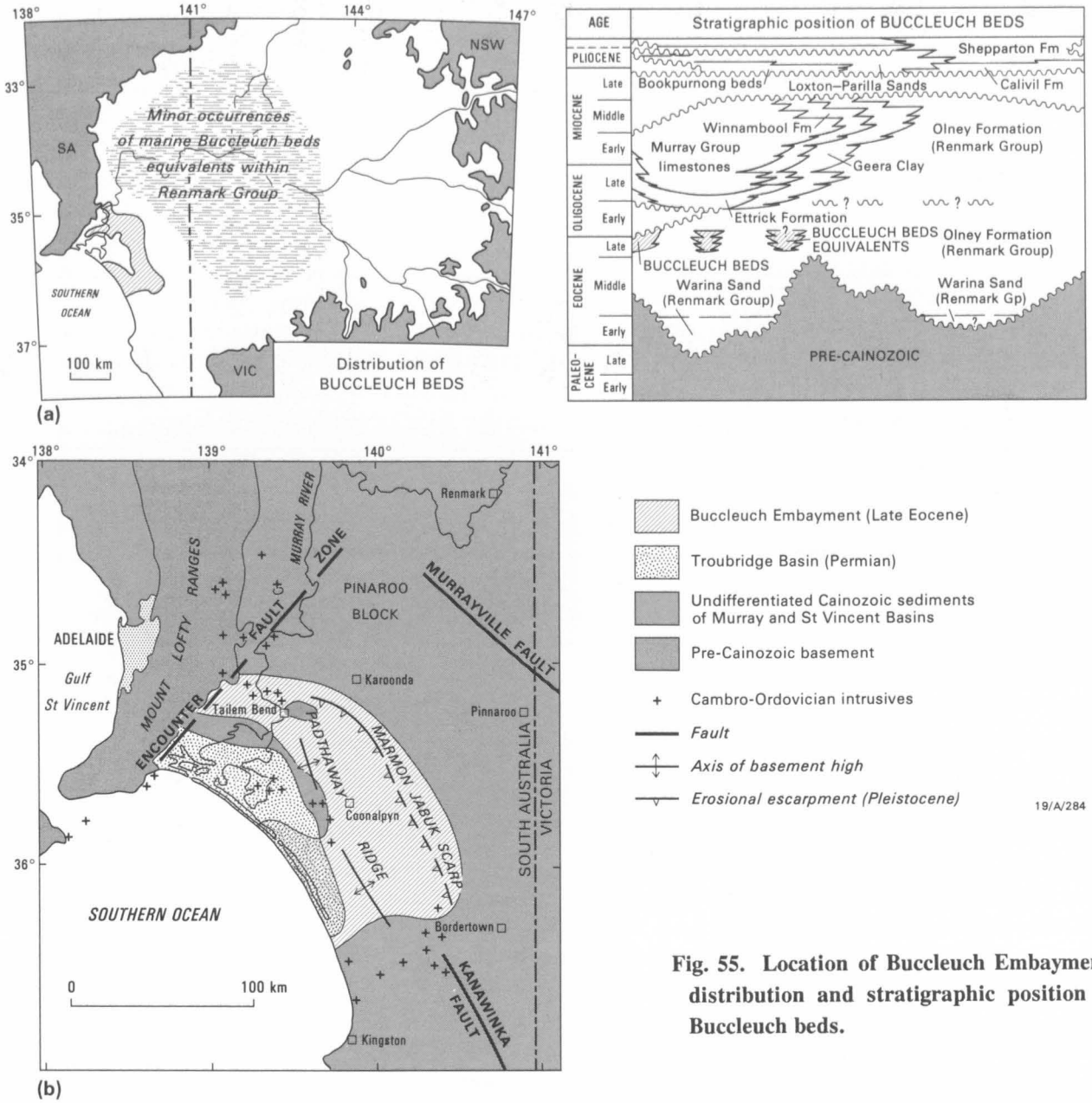


Fig. 55. Location of Buccleuch Embayment; distribution and stratigraphic position of Buccleuch beds.

plain environments, periodically open to the sea (Macphail & Truswell, 1989). Other marine-influenced sediments include thin sands and clays, which occur above the Geera Clay and below the Loxton–Parilla Sands in some bores towards the northern and eastern limits of distribution of the Murray Group sediments (parts of ANABRANCH and BALRANALD). In BMR/DWR (NSW) Woodlands-1 (ANABRANCH), these preserve marginal-marine palynofloras of *Triporopollenites bellus* Zone Middle Miocene age (Macphail, 1988b).

Data sources. Stratigraphic description of the Olney Formation (and equivalent Upper Knight Group and Renmark beds in South Australia) are given in Ludbrook (1957, 1961a, 1963a, 1969a), O'Driscoll (1960), Lawrence (1966, 1975), Harris (1966), Bembrick (1974), Thornton (1974), Lawrence & Abele (1976, 1988), Woolley & Williams (1978), Woolley (1978), Brown (1985), and Brown & Stephenson (1986). Detailed descriptions of core and cutting materials are provided in a number of petroleum exploration well completion reports (e.g. Benbow, 1962; Shiels, 1962; Grasso, 1963, 1964; Laws, 1963; Wright & Stuntz, 1963; Brundall, 1964; Campe & Cundill, 1965; Walter, 1965; Gausden & Watts, 1966; Boyd & Heisler, 1967; Laws & Heisler, 1967; Derrington & Anderson, 1970; Haskell & Wiltshire, 1970). Palynological observations are recorded in Evans (1962), Evans & Hodgson (1963), Harris (1963, 1964, 1966, 1965, 1970, 1971, 1973, 1985), Paten & Price (1970), Harris & Morgan (1976), Martin (1977, 1984a,b,c), Archer (1984),

Macphail (1987, 1988a,b), Truswell (1987), Macphail & Truswell (1988, 1989), and Kellett (1989).

Unit: Buccleuch beds
Age: Late Eocene
Map symbol: Teb
Component units: Buccleuch Bed A, Buccleuch Bed B, Buccleuch Bed C
Synonyms: Buccleuch Beds, Buccleuch Group

Lithology. The Buccleuch beds were subdivided informally by Ludbrook (1957) into three stratigraphic units: Beds A, B, and C (Fig. 54). The lowermost (Bed A) is a highly fossiliferous bryozoal limestone with glauconitic calcareous clay at the base. The intermediate stratum (Bed B) consists of carbonaceous sand, with thin limestone bands. The uppermost unit (Bed C) is a grey-brown carbonaceous clay. Not all beds are necessarily present at any one location, and there are considerable variations in lithology within each bed.

Distribution and thickness. The Buccleuch beds are located within a small embayment in the southwest of the Murray Basin — the Buccleuch Embayment (Fig. 55). The distribution of Buccleuch beds (Fig. 55) is not quite identical to the area of the embayment, because, in the Late Eocene, granitic outcrops of the Padthaway Ridge formed a number of palaeotopographic rises over which the Buccleuch beds were not deposited. The Buccleuch beds have an average thickness of 20–30 m, with a maximum of 78 m recorded (Brown & Stephenson, 1986). The thickest sections occur near the centre of the Buccleuch Embayment.

Some workers have referred other marine sediments of similar age to the Buccleuch beds. For instance, the 'greensands at Kingston' of Ludbrook (1963a,b) were at one stage referred to the Buccleuch beds, but were subsequently reassigned to the Lacepede Formation of the Gambier Embayment of the Otway Basin (Ludbrook, 1971). The Gambier Embayment is contiguous with the Murray Basin in the southern part of NARACOORTE, but Ludbrook (1971) distinguished the Lacepede Formation from the Buccleuch beds on lithology and interpreted sedimentary environment, and stated that the two units were only partly synchronous. Other marine 'Buccleuch beds' sediments associated with the Renmark Group, identified elsewhere in the western Murray Basin, are discussed under 'Remarks'.

Geometry and structure. Buccleuch beds form a lens-like body within the Buccleuch Embayment (Fig. 55); to the west of the Padthaway Ridge they are poorly defined, but increase in thickness towards the continental shelf (see cross-sections C–D and E–F on the enclosed 1:1 000 000 scale geological map).

Stratigraphic relationships. The Buccleuch beds overlie and partly interfinger with the Renmark Group (Olney Formation), and in turn are disconformably to unconformably overlain by Compton Conglomerate or Ettrick Formation. Less commonly, Buccleuch beds may lie directly upon the Ordovician granites of the Padthaway Ridge. Buccleuch beds may also be disconformably to unconformably overlain by Gambier Limestone or Coomandook Formation, although this relationship is not common. The three component Buccleuch beds are conformable to disconformable on older sediments, and the beds themselves are internally conformable, but the sequence is normally complete only in deeper parts of the embayment.

Palaeontology and age evidence. The Buccleuch beds are an entirely subsurface unit, and the macrofauna they preserve is not well known. Bryozoa are abundant, but have not so far been described in detail in the literature. Ludbrook (1957, 1961a) has recorded the echinoid *Australanthus*, the gastropod *Turritella*, and sharks' teeth. Based on the microfauna she concluded that the unit is of Late Eocene age, and was deposited under shallow-marine conditions (Ludbrook, 1957, 1961a).

Lindsay & Bonnett (1973) dated marine 'Buccleuch beds equivalents' near Waikerie as Late Eocene to Early Oligocene, but these sediments possibly form a separate entity from the Buccleuch beds proper (see 'Remarks', 'Renmark Group and 'Olney Formation').

Characteristics. The Buccleuch beds are characterised by their distinct marine lithologies, by stratigraphic position, and by geographical position within the Buccleuch Embayment. The presence of bryozoal and other skeletal material is common and allows the Buccleuch beds to be distinguished from the grey sand of the underlying Renmark Group. Buccleuch Bed B is lithologically similar in some ways to the Renmark Group, but is more highly fossiliferous, and is normally separated from it by the glauconitic calcareous clay of Buccleuch Bed A. Similarly, Buccleuch Bed C is superficially similar to Ettrick Formation, and to the marine facies of Compton Conglomerate. However, Buccleuch Bed C is distinguished from the younger marine formations by its highly carbonaceous content.

Environment of deposition. The Buccleuch beds were deposited in a small marine embayment

(Ludbrook, 1961a). Bed A is a highly fossiliferous bryozoan calcarenite, similar to the later Miocene limestones of the Murray Group; and was succeeded by firstly sand of Bed B, then clay of Bed C, each of which has a large carbonaceous component. The proportion of terrigenous sediments within the Buccleuch beds increases up-sequence. This terrigenous sediment appears to have infilled the Buccleuch Embayment. An Eocene precursor of the Murray River may have been the source, although smaller rivers would also have made some contribution. Bore data suggest that the granites of the Padthaway Ridge formed a series of islands, or archipelago, near the western margin of the Buccleuch Embayment; these may have protected the embayment from the full force of the Southern Ocean.

Stratigraphic nomenclature. The Buccleuch beds were named by Ludbrook (1957) after the County of Buccleuch (South Australia), which partly overlaps their area of distribution. Ludbrook (1957, 1961a). Lindsay & Bonnett (1973) and Rogers (1980a) preferred the name 'Buccleuch Beds', but more recently Lindsay (1985a) used the term 'Buccleuch Group'. However, as the Buccleuch beds have not been formally named (either collectively or individually) in terms of component formations, the term 'Buccleuch Group' cannot yet be regarded as formal.

Type section. The Buccleuch beds are entirely subsurface, and have a standard borehole section (Fig. 54), nominated by Ludbrook (1961a, fig. 4, p.17) – South Australian Engineering and Water Supply Department Bore No.2, Coonalpyn township, Section 56, Hundred of Coneybeer, County Buccleuch (bore 6826-00025 *in* Brown & Stephenson, 1986). In the type section, 53 m of Buccleuch beds overlie Renmark Group, and are in turn overlain by Compton Conglomerate. The section comprises 44.8 m of Bed A, overlain successively by 7.6 m of Bed B, and 0.6 m of Bed C. A detailed description of the lithology and palaeontology of the type section was given by Ludbrook (1961a, p.16–18).

Hydrogeology and economic geology. Both the Murray Group and Pliocene Sands aquifer systems are absent within the Buccleuch Embayment (Fig. 55), leaving the Buccleuch beds aquifer as the only major local source of usable groundwater (although the Pleistocene Padthaway Formation forms a near-surface aquifer in the south of the embayment). The Buccleuch beds aquifer can be treated as equivalent to the Renmark Group aquifer system for most hydrological purposes. Buccleuch Beds B and C include abundant carbonaceous material, but no coal deposits.

Remarks. The Buccleuch beds proper, in the Buccleuch Embayment, were dated as Late Eocene by Ludbrook (1957, 1961a). Lindsay & Bonnett (1973) subsequently assigned marine sediments in the Waikerie area (RENMARK) to Buccleuch beds, but dated these initially as 'middle' Oligocene and subsequently as Late Eocene–Early Oligocene. They noted that the facies present in the Waikerie area differed from the subdivision of Buccleuch beds into Beds A, B, and C within the Buccleuch Embayment (more than 100 km to the south), but observed that a greenish, marly, glauconitic interval occurred at the base of both the Waikerie bores and the type section at Coonalpyn. On the other hand, the white bryozoal limestone, which forms most of Buccleuch Bed A, is absent in the Waikerie bores. Buccleuch Bed B has a facies equivalent in these bores, but is separated from the basal glauconitic marl by a thick 'intermediate (regressive) unit' (Lindsay & Bonnett, 1973, p.18–19), which does not occur in the Buccleuch Embayment sediments. Buccleuch Bed C is also absent in the Waikerie bores.

For the following reasons it is suggested that the sediments encountered in the Waikerie bores do not readily correlate with the Buccleuch beds proper, and may prove to form a separate unit: (1) Lithologies are largely different. (2) The Waikerie bores are spatially separate from the Buccleuch Embayment, with no bores known to intersect Buccleuch beds between the Embayment and Waikerie. Thinner sequences of sediments similar to those at Waikerie have since been found to also occur over a wide area north of the Murray River (Edwards, 1979, 1981a,b, 1982a,b, 1983). (3) The marine-influenced sediments in the Waikerie bores are Eocene–Early Oligocene in age, and are only partly equivalent in age to the Buccleuch beds, and possibly include equivalents of the Oligocene Compton Conglomerate (S. Barnett, S.A.D.M.E., personal communication, 1984). In contrast, the Buccleuch beds of the Buccleuch Embayment are possibly no younger than Late Eocene (Ludbrook, 1957, 1961a). Erosion of Oligocene sediment equivalent to those of the Waikerie area from the Buccleuch Embayment is a possibility. However, borehole data give no evidence of widespread discontinuities between bores within the Embayment; and Buccleuch Beds A, B, and C are readily correlated between boreholes.

In a recent publication, Lindsay & Barnett (1989) have identified correlatives of the Compton Conglomerate and Buccleuch beds, as well as Olney Formation, within the Waikerie sections. Farther to

the northeast, Macphail (1988b) and Macphail & Truswell (1989) identified Middle and Upper *Nothofagidites asperus* Zone dinoflagellates within sediments of the Olney formation in the BMR/DWR (NSW) Woodlands-1 bore (ANABRANCH) and have suggested that these are also marine or coastal plain 'Buccleuch beds equivalents'.

In summary, until further data are available we suggest that the term Buccleuch beds be used to refer only to those Upper Eocene sediments occurring within the marine Buccleuch Embayment on the southwest margin of the Murray Basin, and that the term 'Buccleuch beds equivalents' be reserved for marine or marginal-marine component of equivalent Eocene or Late Eocene–Early Oligocene age, within the Renmark Group.

Data sources. Aspects of the geology of the Buccleuch beds are presented in: Ludbrook (1957, 1961a, 1963a, 1963b, 1971), Carter (1958b), Lindsay & Bonnett (1973), Edwards (1979, 1981a,b, 1982a,b, 1983), Brown & Stephenson (1986), Macphail (1988a,b), and Macphail & Truswell (1989).

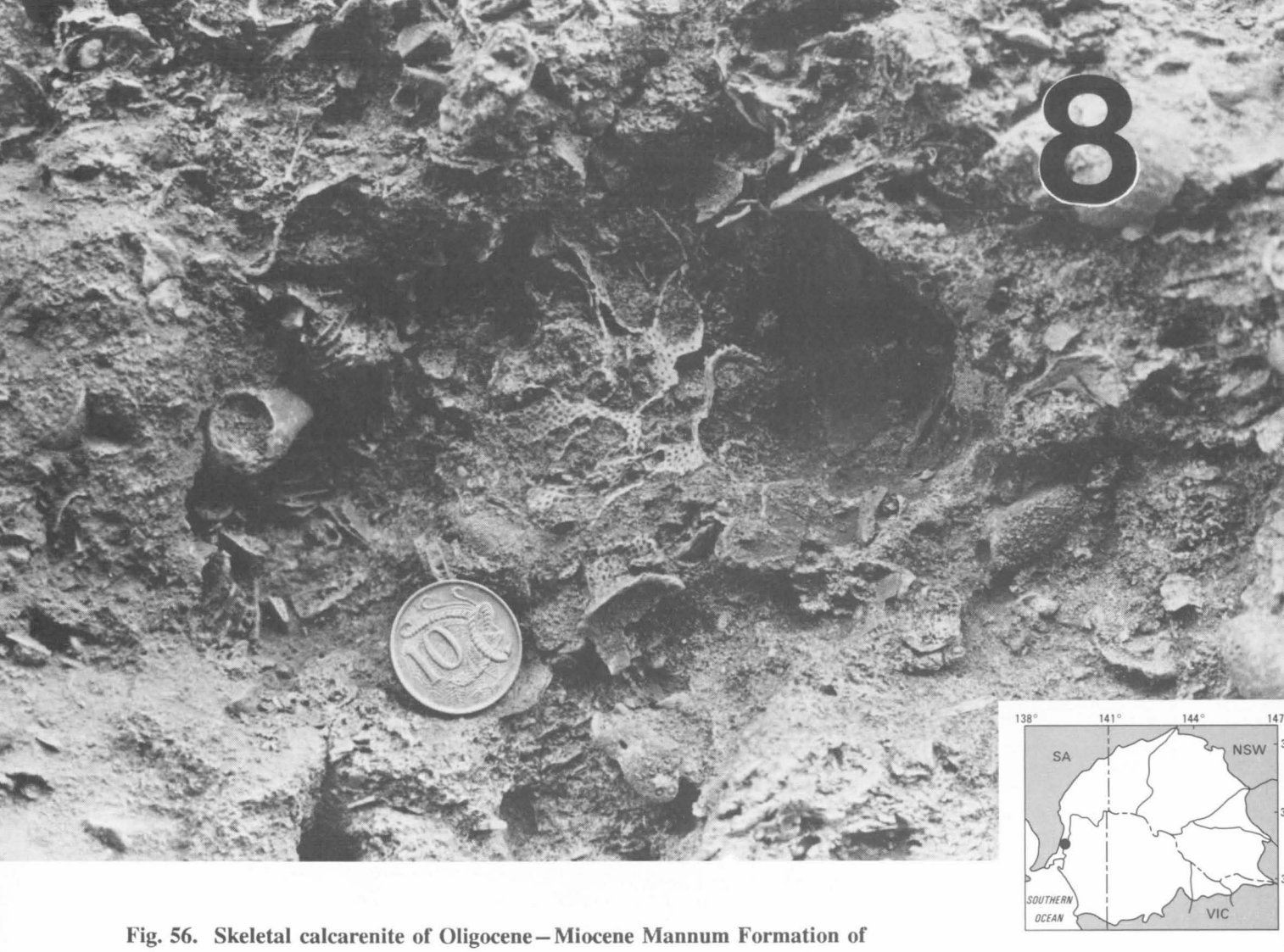


Fig. 56. Skeletal calcarenite of Oligocene–Miocene Mannum Formation of Murray Group, at Mannum Pumping Station (ADELAIDE).

CAINOZOIC STRATIGRAPHY — MID-TERTIARY SEQUENCE

Mid-Tertiary sediments of the marine Murray Group underlie much of the western and south-western Murray Basin. The Group consists mainly of carbonate-dominated formations deposited over an extensive shallow-marine platform. Basal clastics and glauconitic calcareous clay (marl) of the Compton Conglomerate and Ettrick Formation grade upsequence into limestone of the Duddo, Gambier, Morgan and Pata Limestones, and Mannum Formation (Fig. 45). To the north and east, these grade laterally into glauconitic calcareous clay of the Winnambool Formation and terrigenous fine clastics of the Geera Clay. Farther north and east, these marine sediments of the Murray Group interfinger with Oligo-Miocene fluvio-lacustrine and deltaic sediments of the upper part of the Olney Formation of the Renmark Group.

Unit: Murray Group

Age: Oligocene to Middle Miocene

Component units: Compton Conglomerate (Toc), Ettrick Formation (Toe), Yanac Member of the Ettrick Formation (included in Toe; Table 13), Gambier Limestone (part of Tml; Table 15), Naracoorte Limestone Member of the Gambier Limestone (part of Tml; Table 16), Mannum Formation (part of Tml; Table 17), Finniss Clay (included in Tml; Table 18), Morgan Limestone (part of Tml; Table 19), Cadell Marl Lens of the Morgan Limestone (included in Tml; Table 20), Pata Limestone (part of Tml; Table 22), Duddo Limestone (Tml; Table 23), Geera Clay (Tmg), Winnambool Formation (Tmw)

Informal Nomenclature: 'Murray Group limestones', 'Murray Group calcarenites' (Tml)

Definition. The term 'Murray Group' was first defined by Ludbrook (1957), and incorporated several Oligo-Miocene formations in South Australia: the Mannum Formation, Finniss Clay, Morgan Limestone (including the Cadell Marl Lens), and the Pata Limestone (Fig. 57). In Victoria and New South Wales, the Duddo Limestone (Lawrence, 1975) is directly equivalent to the Murray Group. Lawrence (1966) extended the concept of the Murray Group in Victoria to include all post-Renmark Group marine sediments, including the Ettrick Formation, the Geera Clay, the Duddo Limestone, and the Winnambool Formation. Lawrence & Abele (1976, 1988) excluded the Late Miocene–Early Pliocene Bookpurnong beds and Parilla Sand (Vic. nomenclature; equivalent to undifferentiated Loxton–Parilla Sands in the nomenclature of this Bulletin).

The Gambier Limestone is predominantly an Otway Basin formation, which also occurs in the Murray Basin where it conformably underlies younger limestone units of the Murray Group. Ludbrook (1957, 1961a) regarded the Gambier Limestone and the Ettrick Marl (now known as the Ettrick Formation) as formations within the Glenelg Group of Sprigg & Boutakoff (1953), and this terminology remains valid in the Gambier Embayment. However, because of similarities in their lithologies and distribution, the limestone of the Murray Group and the Gambier Limestone are described together in this Bulletin. The term 'Murray Group limestones', as we informally use it, thus includes the skeletal limestone units of the Murray Group as defined by Ludbrook (1957), the Duddo Limestone of Lawrence (1966), as well as the Gambier Limestone (which includes its upper member, the Naracoorte Limestone). This grouping of units is also informally referred to as the 'Murray Group calcarenites'. The various limestone units of the Murray Group are described collectively under 'Murray Group limestones – Tml', and individually in Tables 15, 16, 17, 19, 22 and 23.

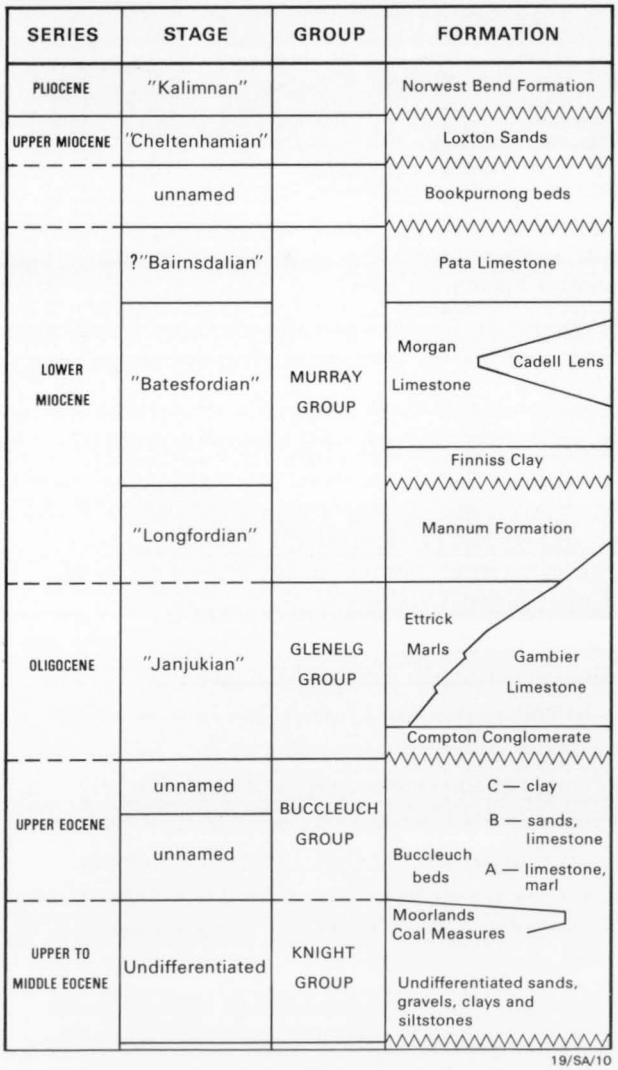


Fig. 57. Ludbrook's (1957) stratigraphic subdivision of the Murray Basin succession in South Australia.

Although the Winnambool Formation and the Geera Clay are parts of the Murray Group, they are peripheral to the main Oligo-Miocene limestone sequence of the Murray Basin, and are described separately, as is the Ettrick Formation; the latter unit belongs to either the Glenelg Group or the Murray Group, depending upon State usage, but is herein included in the Murray Group. For convenience, the Compton Conglomerate (S.A.) and its correlative the Yanac Member of the Ettrick Formation (Vic.) at the base of the succession are also included in the Murray Group.

Unit: Compton Conglomerate
Age: Oligocene
Map symbol: Toc
Synonym: Yanac Member of the Ettrick Formation (Table 13)

Lithology. In its type lithology, the Compton Conglomerate is a partly cemented, medium to coarse-grained conglomerate. The main clasts include ironstone and quartz pebbles, typically within a limonitic matrix. The Compton Conglomerate is, however, a highly variable composite rock unit, and may also occur as dark-brown humic clay, green glauconitic clay, red clay with pebble clasts, or yellow, brown, or grey, poorly fossiliferous calcareous sandstone or calcareous clay. Although the Compton Conglomerate has a very restricted stratigraphic position and was deposited over a short interval of

time, these extreme variations in lithology occur because it was deposited in several different environments.

Distribution and thickness. The distribution of the Compton Conglomerate is very patchy. Within the Murray Basin, it is known at only one outcrop (Lindsay & Williams, 1977); the type section, in the Gambier Embayment of the Otway Basin, is the only known outcrop in that basin. The Compton Conglomerate occurs most commonly within the Buccleuch Embayment (Fig. 55), where its presence has been identified in 28 out of 227 boreholes examined (Brown & Stephenson, 1986); its distribution within this embayment is fairly random. Compton Conglomerate is rarely found elsewhere in the Murray Basin, having been identified in a total of only 21 boreholes in South Australia outside the Buccleuch Embayment (Brown & Stephenson, 1986), although it appears to occur slightly more commonly near the western margins of the basin. Equivalents of Compton Conglomerate occur in parts of western Victoria (Yanac Member of the Ettrick Formation), but the unit has not been identified in northern and eastern areas of the Murray Basin.

The thickness of the Compton Conglomerate is highly variable: it is absent in most boreholes, but where present commonly ranges from 1 to 7 m. A maximum verified thickness of 16 m has been recorded (Brown & Stephenson, 1986), although Firman (1972) records 30 m of 'Compton Conglomerate equivalent' in one isolated location on RENMARK. This rock unit consists of quartz and ironstone gravel, and is situated near the western margin of the basin: it is possibly an outwash deposit from the Mt Lofty Ranges, which may be approximately time-equivalent to the Compton Conglomerate.

Palaeontology and age evidence. In areas where the Compton Conglomerate is of marine provenance, it preserves a sparse macrofauna which includes fragments of brachiopod shells and bryozoa. An impoverished foraminiferal assemblage was described briefly by Ludbrook (1961a), who assigned an Oligocene age to the microfauna. Ludbrook (1961a) stated that Compton Conglomerate disconformably overlies the upper member of the Buccleuch beds; a unit to which she assigned a Late Eocene age. The Compton Conglomerate is overlain with apparent conformity by Ettrick Formation, dated as Oligocene by Ludbrook (1957, 1961a) on foraminiferal evidence, and now thought to be of Oligocene to Early Miocene age. Stratigraphic evidence thus suggests that the Compton Conglomerate is of late Early to early Late Oligocene age. Lindsay & Williams (1977) described an outcrop of Compton Conglomerate, or its close equivalent, from the Cross's Bridge section on BARKER (see Fig. 59 and 'Ettrick Formation') and dated overlying Ettrick Formation as "early to middle Oligocene". At the nearby Hartley road cut and Kalibar railway cutting (BARKER; see Figs 59, 60), they identified *Massilina torquayensis* (Chapman) suggesting an Oligocene age. They also examined material from a nearby bore (Paragum-1) and noted the presence of *Massilina torquayensis*, *Guembelitria stavensis* Bandy and *Bolivinopsis cubensis* (Cushman & Bermudez), in addition to the absence of *Chiloguembelina cubensis*, and concluded that the foraminiferal fauna of the unit at that site indicated an Oligocene (and probably Late Oligocene) age. In areas where the Compton Conglomerate is of terrigenous provenance, a well-developed oxidized surface is present (Lawrence, 1966). This indicates that sufficient time had elapsed since the deposition of the underlying Renmark Group and Buccleuch beds for a mature pedogenic surface to develop. The age of the Compton Conglomerate is therefore interpreted to be predominantly late Early Oligocene to early Late Oligocene.

Characteristics. The Compton Conglomerate is characterized by its stratigraphic position and lithology, even though the latter is quite diverse. The unit is typified by the presence of either (a) a ferruginous matrix containing pebble clasts, or (b) a glauconitic clay or sand. Both of these lithologies contrast with the grey sand or brown carbonaceous sediments of the Renmark Group. Differentiating the Compton Conglomerate from the overlying Ettrick Formation is not always easy, particularly where each unit is a glauconitic calcareous clay – such clay has generally been included in the Ettrick Formation.

Environment of deposition. The Compton Conglomerate is a composite unit, and marks the first accumulation of marine sediments after – and probably non-marine during – an Early Oligocene period of mainly sub-aerial erosion and/or non-deposition. In the southwest, the Compton Conglomerate lies disconformably upon sediments of the Renmark Group, and there is evidence from some boreholes in Victoria (Lawrence, 1966) and South Australia (O'Driscoll, 1960; Brown & Stephenson, 1986) that a pedogenic surface was developed at the top of these sediments. Where the Compton Conglomerate has taken the form of a ferruginous gravel or laterite, it is probably of residual terrestrial rather than marine origin (O'Driscoll, 1960). In other areas, the Compton Conglomerate represents the

basal unit deposited during a rapid marine transgression, which probably occurred during the late Early Oligocene (see 'Cainozoic Sedimentation Patterns'). Micropalaeontological evidence suggests that the lower boundary of the Compton Conglomerate is mainly synchronous (Lawrence, 1966).

Stratigraphic nomenclature. The Compton Conglomerate derives its name from the settlement of Compton, near Mount Gambier, South Australia. The Compton Conglomerate was included in the Glenelg Group of Sprigg & Boutakoff (1953) by Ludbrook (1957). In Victoria, equivalents of the Compton Conglomerate were described by Lawrence (1966) as the Yanac Member of the Netherby Marl. Lawrence (1975) later recognised that the Netherby Marl was the same formation as the Ettrick Marl of Ludbrook (1957), so that the Yanac Member became a subdivision of the Ettrick Marl (now Ettrick Formation – Ludbrook, 1963a).

Type section. Ludbrook (1961a) designated the exposure in 'Knights Quarry', located in Section 718, Hundred of Blanche, County Grey, near Compton in South Australia, as the type section of the Compton Conglomerate. However, she later reported that the quarry had never been owned by the Knight family, and was locally known as 'Allens Quarry' (Ludbrook, 1971). Waterhouse (1977) subsequently noted that the quarry is located in Section 715, rather than in Section 718. The type section thus lies within the Gambier Embayment of the Otway Basin (Wopfner & Douglas, 1971), rather than the Murray Basin, and is located on PENOLA at the southern margin of the enclosed 1:1 000 000 scale geological map. The type section (Fig. 51) is some 0.5 m thick, consists of abundant ironstone pebbles and grit in a limonitic matrix, and has a poor microfauna (Ludbrook, 1961a). The section unconformably overlies the 'Knight Group' (equivalent to the Renmark Group in the Murray Basin), and passes conformably upwards into the Gambier Limestone.

Stratigraphic relationships and correlations. The Compton Conglomerate disconformably overlies the Renmark Group (Olney Formation), and the Buccleuch beds, and is in turn conformably overlain by the Ettrick Formation, and by the Gambier Limestone (Duddo Limestone in Victoria) in areas where the Ettrick Formation is absent. Firman (1972) records possible 'Compton Conglomerate equivalents' directly overlying Cambrian basement on RENMARK. The Compton Conglomerate occurs in a similar stratigraphic position in both the Otway and Murray Basins, and reflects the same transgressive event. In the South Australian part of the Otway Basin, depending upon the degree of erosion of Eocene sediments, the Compton Conglomerate unconformably overlies either the Lacepede Formation, the Kongorong Sand, or the Tartwaup Formation (Ludbrook, 1971; Waterhouse, 1977), and is in turn overlain by the Gambier Limestone, which in the Otway Basin is partly an equivalent of the Ettrick Formation in the Murray Basin.

Remarks. The Compton Conglomerate was deposited during, and after, a period of erosion and/or non-accumulation of sediments, and was associated with a rapid marine transgression. On palaeontological and stratigraphic evidence, the Compton Conglomerate is thought to be of 'early to mid'-Oligocene age. The pre-Compton erosional and pedogenic surfaces possibly correlate with a major fall in global relative sea-level during the Early Oligocene, until about 30/32 Ma (Vail & others, 1977; Loutit & Kennett, 1981); deposition of marine components of the Compton Conglomerate and succeeding Ettrick Formation is correlated with the subsequent late Early Oligocene rise in relative sea-level. The lateritic ferruginised surface, which is locally preserved at the top of the Renmark Group in southwestern areas, suggests that there was a hiatus prior to the deposition of marine components of the Compton Conglomerate until about 30/32 Ma. An absolute age for the formation is difficult to ascertain in the absence of detailed palaeontological dating, but we suggest that some ferruginised, non-marine components may have been deposited prior to 30 Ma, whilst deposition of marine components probably occurred between 30–26 Ma.

Data sources. Descriptions of the Compton Conglomerate are provided in: Sprigg & Boutakoff (1953), Ludbrook (1957, 1961a, 1963a, 1971), O'Driscoll (1960), Lawrence (1966, 1975), Kenley (1971), Firman (1972), Waterhouse (1977), Lindsay & Williams (1977), and Brown & Stephenson (1986).

Unit: Ettrick Formation of the Murray Group
Age: Oligocene to Early Miocene (mainly Oligocene)
Map symbol: Toe
Member: Yanac Member (Table 13)
Synonyms: Ettrick Marls, Ettrick Marl, Netherby Marl

Lithology. The Ettrick Formation consists mainly of grey and green, highly fossiliferous calcareous clay (mainly described as marl in borelogs). In places, the calcareous clay has a high content of quartz sand and skeletal debris, locally grading into sandy skeletal clay and calcareous silt. In many bores, thin inter-

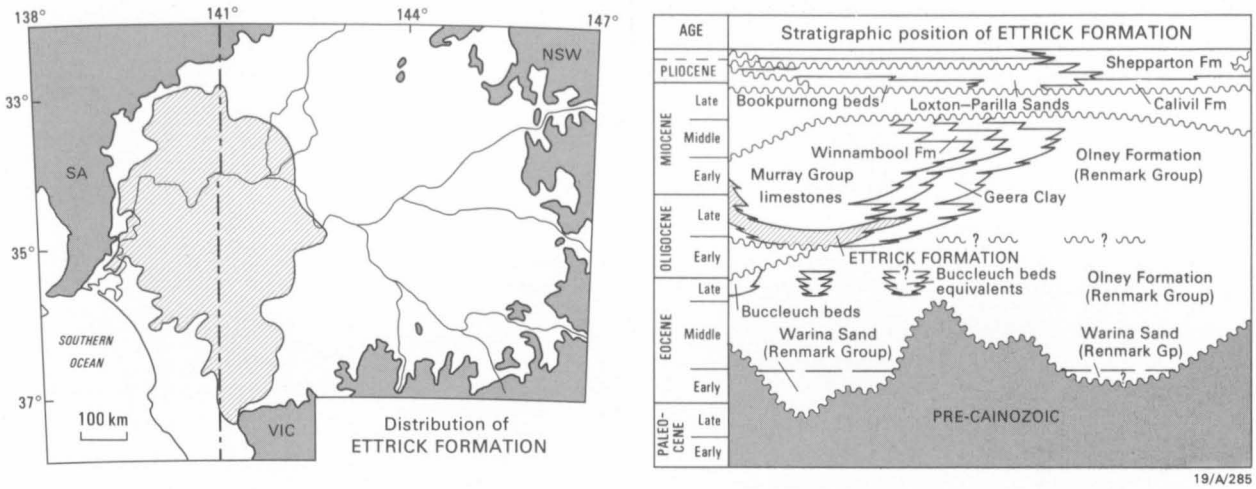


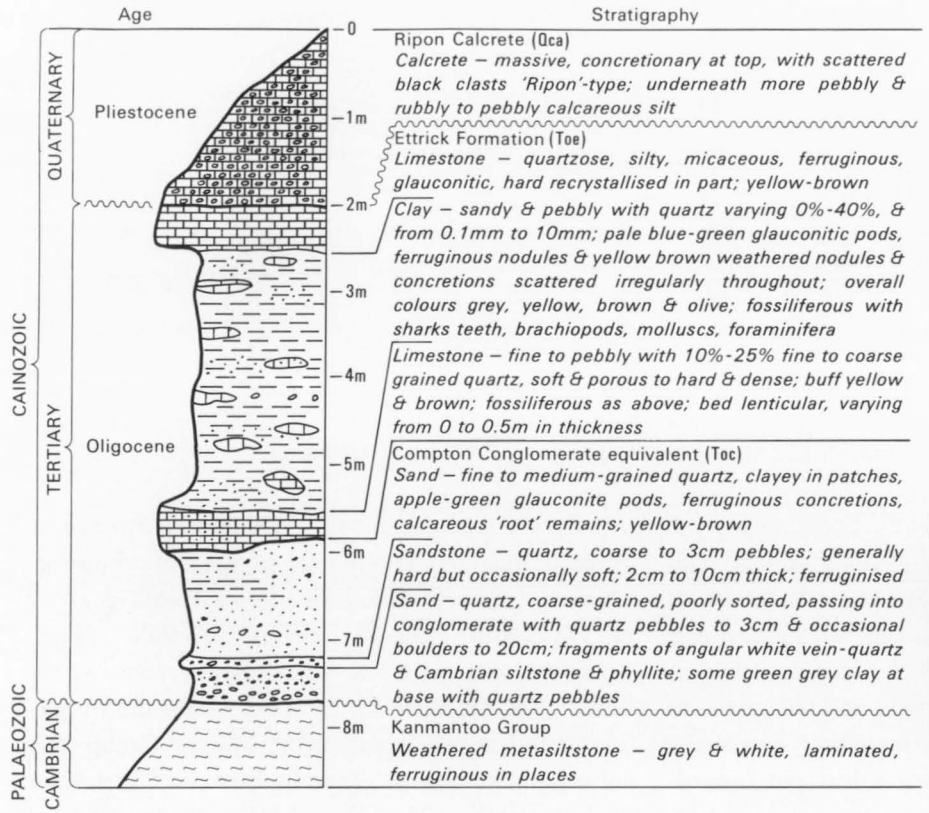
Fig. 58. Distribution and stratigraphic position of Ettrick Formation.

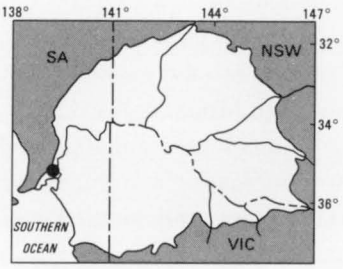
calations of dense grey calcilutite occur within the calcareous clay. Interbeds of friable skeletal calcarenite are increasingly common towards the top of the unit. Moderately calcareous clay is generally dark grey in colour, grading through blue-grey to pale grey with increasing calcareous content, and pale green to dark green and mottled with increasing glauconite content. The unit is increasingly calcareous towards central and southwestern parts of the basin, and increasingly argillaceous towards the east and north. Lawrence (1975), for example, noted that the formation is increasingly calcareous towards northwestern Victoria. The formation is lithologically more variable towards the base, with minor interbeds of fossiliferous quartz sand and thin intercalations of carbonaceous clay. In the Waikerie area, Lindsay & Bonnett (1973) recorded a basal glauconitic clay, which is 6–10 m thick and consists of compact, non-calcareous, dark-grey, glauconitic, pyritic silty clay with shell fragments and green and grey faecal pellets. Firman (1973) noted that the basal components are particularly glauconitic, although the formation is characterised by detrital and authigenic glauconite throughout. It normally also contains a high content of both disseminated and aggregated pyrite, as well as less common micritic nodules and dark-grey chert. The fine-grained sand and silt-size intraclasts, which occur within the calcareous clay, consist of detrital particles of micrite, skeletal debris, angular quartz grains and glauconite. The carbonate matrix consists mainly of calcite, but aragonite has also been detected; the associated allogenic clays include kaolinite and illite, and goethite is also present (Lawrence, 1975). The presence of alunite bands and lenses has been reported from a road-cut near Hartley (BARKER; Lindsay & Williams, 1977).

Distribution and thickness. The Ettrick Formation forms a thin, but continuous blanket of sediment, which extends within western and southwestern areas of the basin beneath western Victoria, South Australia, and parts of southwestern New South Wales (Fig. 58; Plate 7). In areas where the formation underlies limestones of the Murray Group it is uniformly thin, and is generally between 20 to 30 m thick, averaging 24 m in 302 bores recorded by Brown & Stephenson (1986). In southwest Victoria, Lawrence (1975) recorded thicknesses of over 60 m in some bores on HORSHAM, where the limestone sequence is largely absent, but the 'Ettrick Formation' is probably a composite of Oligo-Miocene Ettrick and Winnambool Formations and Duddo Limestone (see 'Remarks').

Outcrop. The formation is entirely concealed beneath western Victoria and southwestern New South Wales. In South Australia, the unit is also mainly concealed but minor occurrences of calcareous clay (marl), thought to be Ettrick Formation, are exposed in sections near Hartley (BARKER) at the up-faulted southwestern margins of the basin (Fig. 59). A 4 m thick section exposed in a river cliff section near Cross's Bridge, for example, consists of glauconitic quartzose clay with thin limestone bands and lenses, and a 2.5 m thick section exposed in the Hartley road-cut is quartzose and sandy, indicating proximity to a near-shore environment (Lindsay & Williams, 1977). The unit has also been interpreted in a railway cutting at Monarto (Fig. 60), and is also locally visible in river cliff sections on the east bank of the Murray River between Tailem Bend and Wellington, where it atypically consists of hard grey limestone with chert nodules or green-brown glauconitic quartzose limestone (Ludbrook, 1961a;

Section exposed in bank of Bremer River at Cross's Bridge





Section exposed in roadcut near Hartley

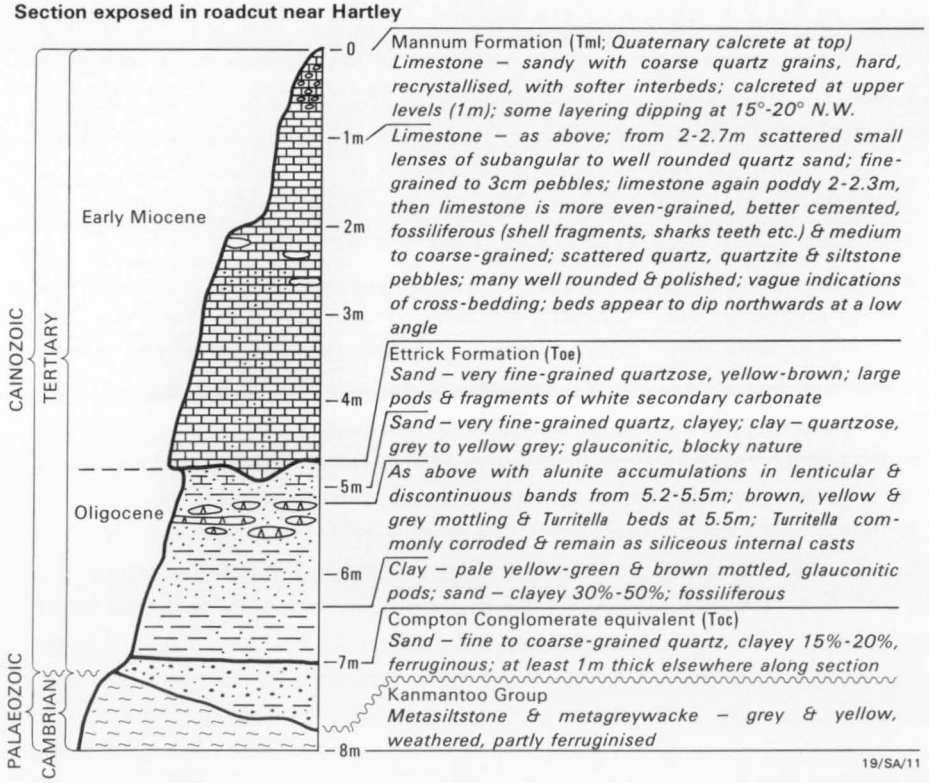


Fig. 59. Exposures of Ettrick Formation at Cross's Bridge and Hartley road-cut, southwestern Murray Basin (BARKER 1:250 000 and Monarto 1:50 000 Sheets); grid reference of Cross's Bridge section is 318650/6104000; grid reference of Hartley road cut section is 318850/4105100; based on Lindsay & Williams, 1977).

TABLE 13. OLIGOCENE YANAC MEMBER OF THE ETTRICK FORMATION

Unit: Yanac Member of Ettrick Formation

Age: Oligocene

Map symbol: included in Toe

Synonyms: Compton Conglomerate

Lithology. Fossiliferous, green or orange, glauconitic, micaceous clay, sand; grade up-sequence into grey calcareous clay of Ettrick Formation. Basal clay characteristically ferruginised and orange/red-brown. Contains material reworked from underlying Olney Formation. In Vic.D.M. Warraquil No.3 (Fig. 62) Lawrence (1966, 1975) identified chamositic oolites within sideritic micritic matrix.

Remarks. Patchy distribution in SW Victoria, where thicknesses of only few metres in water bores. Lawrence (1975) placed basal 5 m in Vic.D.M. Warraquil No.3. (Fig. 62) in Yanac Member. Can be directly correlated with Compton Conglomerate at base of Murray Group in S.A.; neither unit well-defined, but Compton Conglomerate considered to be separate, distinct unit, not everywhere associated with Ettrick Formation. Suggest that, where feasible, name 'Yanac Member of Ettrick Formation' be replaced by Compton Conglomerate.

Data sources. Lawrence (1966, 1975).

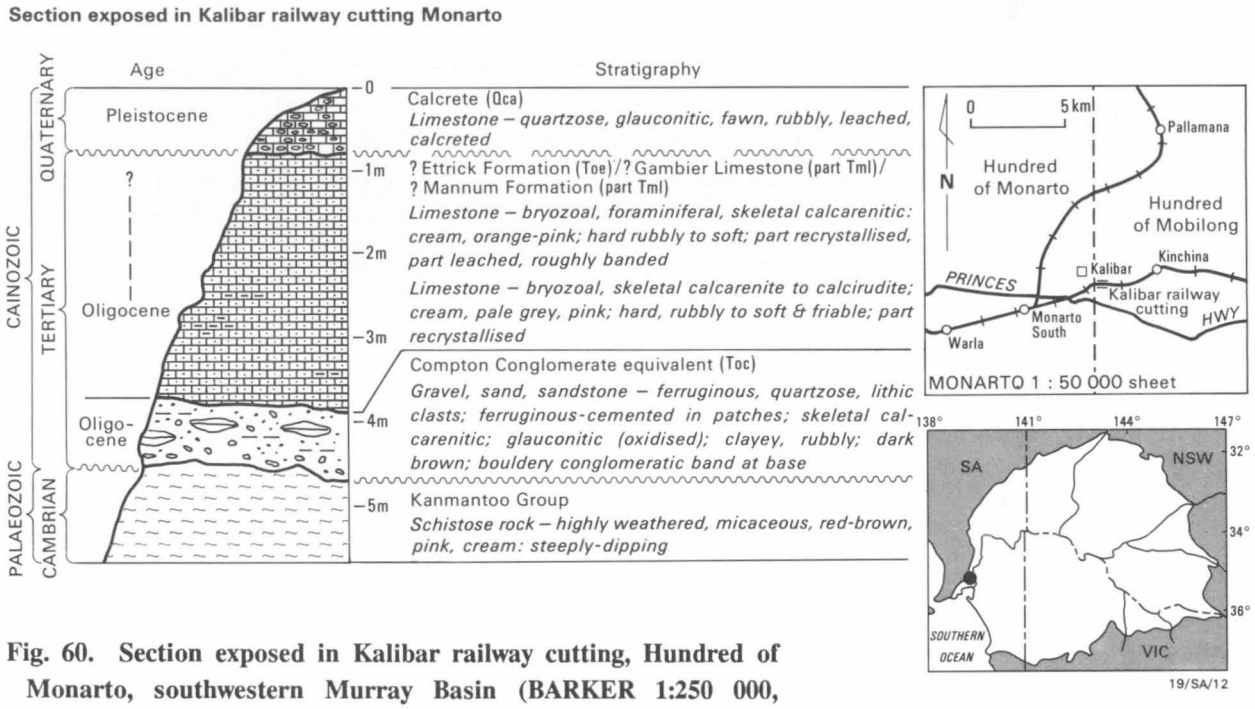


Fig. 60. Section exposed in Kalibar railway cutting, Hundred of Monarto, southwestern Murray Basin (BARKER 1:250 000, MONARTO 1:50 000 – grid reference 332900/6112700); interpreted as exposure of Ettrick Formation (after Lindsay & Williams, 1977).

Lindsay & Williams, 1977). Ludbrook (1961a) also correlated exposures of bryozoal limestone near Coonalpyn (Chapman, 1943) and green sandy marl in the Elwomple area (Hundred of Seymour) with the Ettrick Formation.

Internal geometry and log characteristics. The Ettrick Formation forms a thin flat-lying veneer of sediment, beneath the southwestern part of the basin. In some bores, the unit is finely laminated, but elsewhere it is heavily bioturbated with little preservation of internal structure. Dense, resistant micritic intercalations are thinly bedded with thicknesses of only a few centimetres. Soft skeletal calcarenite and calcisiltite interbeds are also generally only a few centimetres thick.

The Ettrick Formation is relatively distinctive on geophysical well logs in boreholes, where it is overlain by calcarenites of the Murray Group and underlain by sediments of the Renmark Group. In response to the high content of glauconite, gamma-log profiles are characterised by high-count spikes. The formation also exhibits lower resistivity values, and more positive self-potential profiles in comparison with overlying calcarenite formations.

Palaeontology. The Ettrick Formation contains an abundant and diverse assemblage of marine fossils. The dominant components are bryozoans, molluscs, echinoids, foraminifera, hystrichosphaeres and dinoflagellates. Foraminiferal assemblages include miliolids. The foraminifera *Massilina torquayensis* characteristically occurs towards the base of the formation (Ludbrook, 1957; Firman, 1973), and the foraminifera *Guembelitria stavensis* is generally present throughout the formation (Lawrence, 1975).

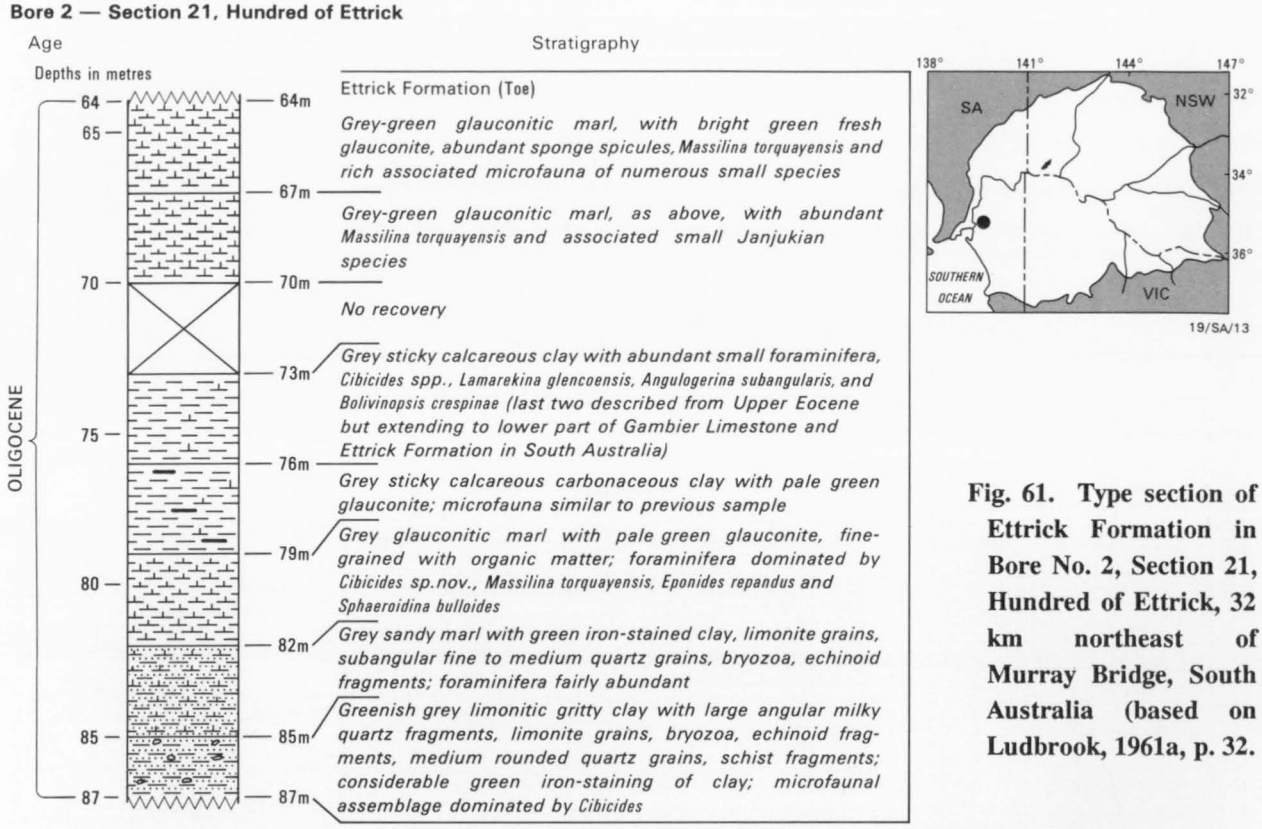


Fig. 61. Type section of Ettrick Formation in Bore No. 2, Section 21, Hundred of Ettrick, 32 km northeast of Murray Bridge, South Australia (based on Ludbrook, 1961a, p. 32.

Age evidence. Foraminiferal assemblages indicate that the Ettrick Formation is predominantly of Oligocene to Early Miocene age. The stratigraphic position of the unit below the Murray Group limestone formations suggests that it is mainly Oligocene in age in the southwest and only extends into the Miocene farther north and east. The presence of *Guembelitria stavensis* and absence of *Chiloguembelina cubensis* is thought to be indicative of Janjukian Stage (Ludbrook, 1957, 1958a, 1961a) equivalent to Zone 5 of Carter (1958a,b). Lindsay & Bonnett (1973) identified *Globigerina angulisaturalis* of Late Oligocene to Early Miocene Zone 2 to 4 age in bores near Waikerie. At the Cross's Bridge river cliff exposure (Fig. 59), Lindsay & Williams (1977) identified a foraminiferal assemblage which included common *Massilina torquayensis*, occasional *Planorbulina* sp., frequent planktonic species *Guembelitria stavensis* and rare planktonic *Chiloguembelina cubensis*, *Globigerina labiacrassata*, *Globigerina (Subbotina) angiporoides* and *Tenuitella gemma*. This assemblage was interpreted to be of 'early to middle' Oligocene age. The section is, however, located at the basin margin – is only 4 m thick, and is underlain by 2 m of Compton Conglomerate over Cambrian Kanmantoo metasediments – suggesting the possibility that the section may include re-worked materials. At a nearby site, farther to the northeast, in the railway cutting near Monarto (Fig. 60), Lindsay & Williams (1977) noted the common presence of *Guembeletria stavensis* and absence of *Chiloguembelina cubensis* in skeletal calcarenites (tentatively correlated with Ettrick Formation) overlying Compton Conglomerate. The foraminiferal assemblage was interpreted as lower Janjukian (Upper Oligocene).

Beneath the overlying limestone unit, the upper surface of the Ettrick Formation is largely synchronous and of Late Oligocene age. In southwestern Victoria, however, deposition of the formation extended into the *Globigerina euapertura* zone, indicating that the upper surface of the formation is locally diachronous (Abele, 1976, 1988). In this area, the limestone of the Murray Group is partly absent, and the Ettrick Formation is significantly thicker than elsewhere (Lawrence, 1975; Brown & Stephenson, 1986). These younger components are partly age-equivalent to the lithologically similar Oligo-Miocene Winnambool Formation, and the thick sequence is probably a composite of Ettrick and Winnambool Formations and intercalated Duddo Limestone. In SADME Oakvale No.1 bore in OLARY in the northwest, Lindsay (1983a) also assigned Oligo-Miocene calcareous clays and marls to the Ettrick Formation, rather than to the Winnam-

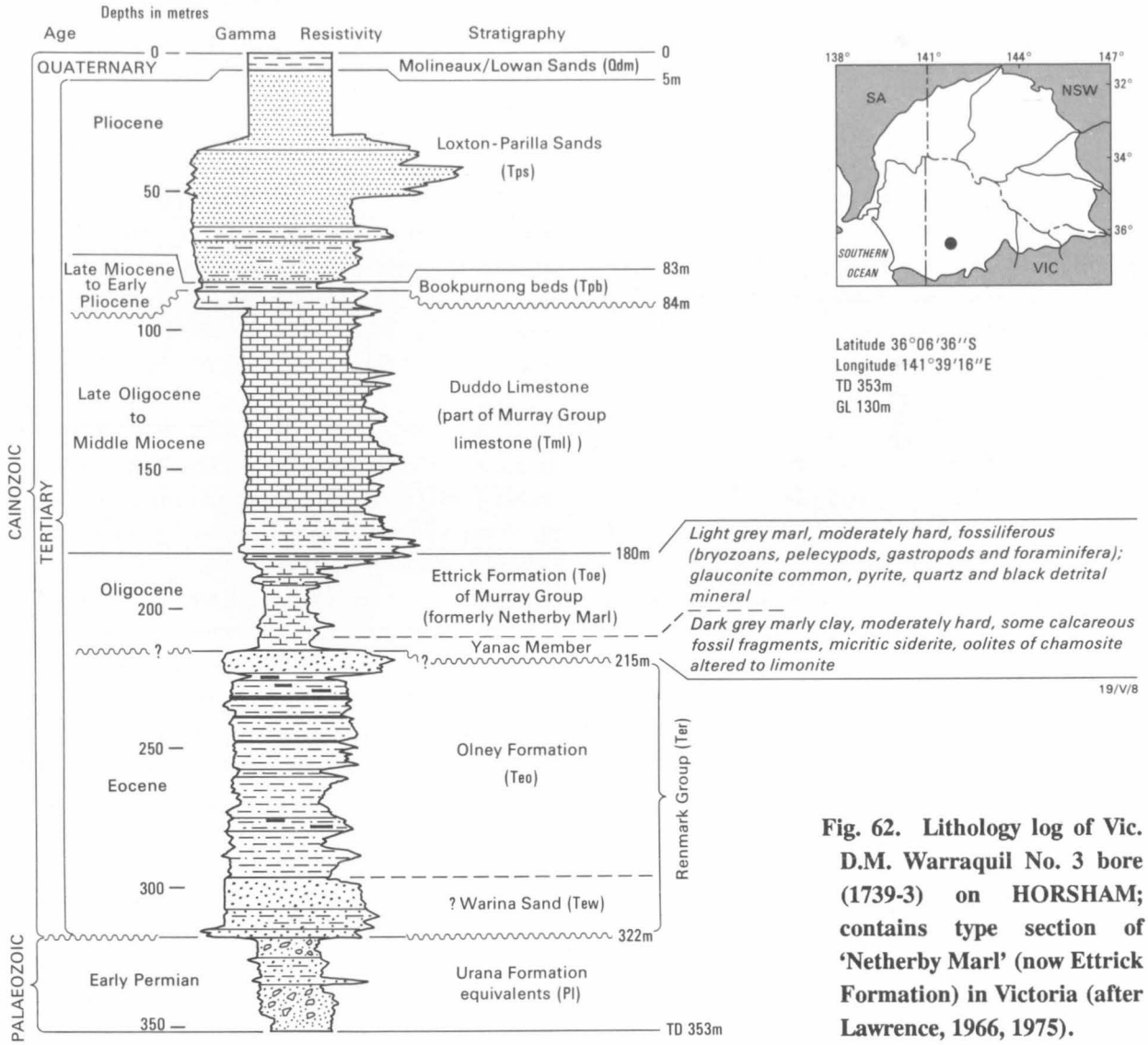


Fig. 62. Lithology log of Vic. D.M. Warraquil No. 3 bore (1739-3) on HORSHAM; contains type section of 'Netherby Marl' (now Ettrick Formation) in Victoria (after Lawrence, 1966, 1975).

bool Formation (see 'Remarks').

Characteristics. The Ettrick Formation characteristically consists of highly glauconitic, calcareous clay and is generally lithologically distinct from underlying and overlying stratigraphic units. Locally in the southwest, it is lithologically similar to the underlying Eocene Buccleuch beds, and towards the northern and eastern limits of its distribution is lithologically identical to the younger Winnambool Formation. The Ettrick Formation is, however, more widely distributed and lithologically more variable than the Winnambool Formation. It is also predominantly Oligocene in age rather than Late Oligocene–Middle Miocene.

Interpretation of environment of deposition. The presence of glauconite, abundant marine fossils and skeletal debris indicates that the unit was deposited primarily in a shallow-marine shelf environment. The presence of unwinnowed calcareous clay and micritic limestone with intercalated beds of highly fragmented skeletal debris suggests deposition in relatively low-energy environments, with intermittent deposition under high-energy catastrophic conditions. Glauconitic clay at the base of the Ettrick Formation at Waikerie (Lindsay & Bonnett, 1973) preserves arenaceous foraminifera, including *Cyclammina* and ?*Hoplophragmoides*, which are indicative of an initial restricted-marine environment, whereas some thin intervals up-sequence have *Globigerina angulisuturalis*, thought to be indicative of an open-marine environment. In summary, therefore, the formation was deposited over a shallow-marine shelf, in low-energy, environments, which ranged from 'deeper-water' marine in southwestern areas, to restricted-marine shelf and lagoonal farther east and north. The formation was

deposited during the initial stages of a major late Early Oligocene–Middle Miocene marine transgression, which flooded western and southwestern areas of the Murray Basin (Ludbrook, 1957, 1969a; Brown, 1983, 1985).

Stratigraphic nomenclature. The name of the formation is derived from County Ettrick in southeast South Australia (Ludbrook, 1957).

Synonyms. In South Australia, the formation was originally thought to consist primarily of calcareous clay (marl) and was named 'Ettrick Marls' by Ludbrook (1957). Later investigations showed that the formation also includes sandy beds and limestone intervals: hence, Ludbrook (1961a) subsequently altered the name to 'Ettrick Formation'. In Victoria, equivalent sediments were initially named 'Netherby Marl' by Lawrence (1966) and subsequently renamed 'Ettrick Marl' by Lawrence (1975). In New South Wales, the name 'Ettrick Marl' was adopted by Woolley & Williams (1978). In this Bulletin, we suggest that the name 'Ettrick Formation' of Ludbrook (1961a) be adopted throughout the basin in preference to 'Ettrick Marl'. Where possible, calcareous clay/marl of Oligocene age, underlying the Murray Group limestone formations within the southwest of the basin, should be placed in the Ettrick Formation. It is also suggested that lithologically similar sediments of Late Oligocene–Miocene age, which are laterally intercalated with (rather than underlying) the limestone formations, be placed in the Winnambool Formation.

In Victoria, Lawrence (1966) defined the basal Yanac Member (Table 13) of the Ettrick Formation ('Netherby Marl'). This member is a partly synonymous correlative of the Compton Conglomerate in South Australia.

In South Australia, Ludbrook (1957) included the Ettrick Formation in the 'Glenelg Group' of Sprigg & Boutakoff (1953), whereas Lawrence (1966) included the stratigraphically equivalent 'Netherby Marl' in the Murray Group. This later convention is followed in this Bulletin.

Type section. Ludbrook (1957) nominated a 21 m thick section in borehole No.2, Section 21, Hundred of Ettrick, 30 km E.N.E. of Murray Bridge, as the type section. The formation occurs between 64 m and 85 m. The basal 5 m consists of greenish-grey glauconitic marl (calcareous clay) stained with ferric iron which weathers to limonite; the next 9 m up-sequence consists of light-grey marl, and the remaining 7 m of grey-brown marl (Fig. 61; Ludbrook, 1961a). In Victoria, Lawrence (1966) nominated the interval between 180 m and 215 m in Vic. D.M. Warraquil No.3 bore as the type section of the stratigraphically equivalent, synonymous, Netherby Marl (Fig. 62).

Stratigraphic relationships. In the southwest of the basin, the Ettrick Formation conformably overlies, and interfingers with, Oligocene sediments of the Compton Conglomerate. Elsewhere the formation probably disconformably overlies Eocene to Lower Oligocene components of the Renmark Group, though farther east and north it (and younger diachronous equivalents of the Winnambool Formation) conformably overlies and interfingers with Oligocene–Miocene components. In Vic. D.M. Olney No.1 and Warraquil No.3, for example, Abele (1970) identified Janjukian foraminiferal assemblages within both the base of the Ettrick Formation and the top of the underlying Olney Formation. Similarly, Archer (1984) could find no significant break at the top of the Olney Formation. The Oligocene Ettrick Formation, therefore, in part conformably overlies Oligocene components of the Renmark Group. As indicated previously (see 'Renmark Group'), the Olney Formation is a composite unit consisting of Eocene and Oligo-Miocene components, and hence in some southwestern areas the Ettrick Formation disconformably overlies the older components of the Olney Formation.

To the south, the Ettrick Formation is laterally equivalent to part of the Gambier Limestone, but elsewhere it is generally conformably overlain by limestone formations of the Murray Group. Towards the north and east, the formation grades laterally into the Geera Clay and up-sequence into the lithologically similar, but younger, Winnambool Formation. In southwest Victoria, where deposition of the Ettrick Formation continued into the Miocene (Lawrence, 1975), the formation interfingers with the limestone of the Murray Group. As noted above, these sediments are similar in age and lithology to sediments assigned elsewhere to the Winnambool Formation.

Aquifer characteristics. The calcareous clay and dense micritic limestone of the Ettrick Formation form part of the mid-Cainozoic Lower confining layer (see Fig. 172), which in western areas of the basin separates the Renmark Group aquifer system from the Murray Group aquifer system. Water in the formation is generally highly saline.

Remarks. In places, the calcareous clay of the mainly Oligocene Ettrick Formation can be confused with younger, lithologically similar sediment of the mainly Miocene Winnambool Formation. Thus, the Ettrick Formation and Winnambool Formation should probably be regarded as parts of one and the same time-transgressive unit. They are almost impossible

to distinguish on lithology alone, but, whereas the Ettrick Formation underlies almost the entire southwest of the basin (Fig. 58), the Winnambool Formation is confined in distribution to an arcuate zone underlying the west-central part of the basin (see Fig. 81). Thus, distribution and age are criteria that can be applied to distinguish the formations in most areas. Where practicable, it is suggested that Oligocene calcareous clay be assigned to the Ettrick Formation, and Miocene equivalents be assigned to the Winnambool Formation. In some bores in northern South Australian and southwest Victorian parts of the basin, Miocene calcareous clay (marl), which we now believe to be parts of the Winnambool For-

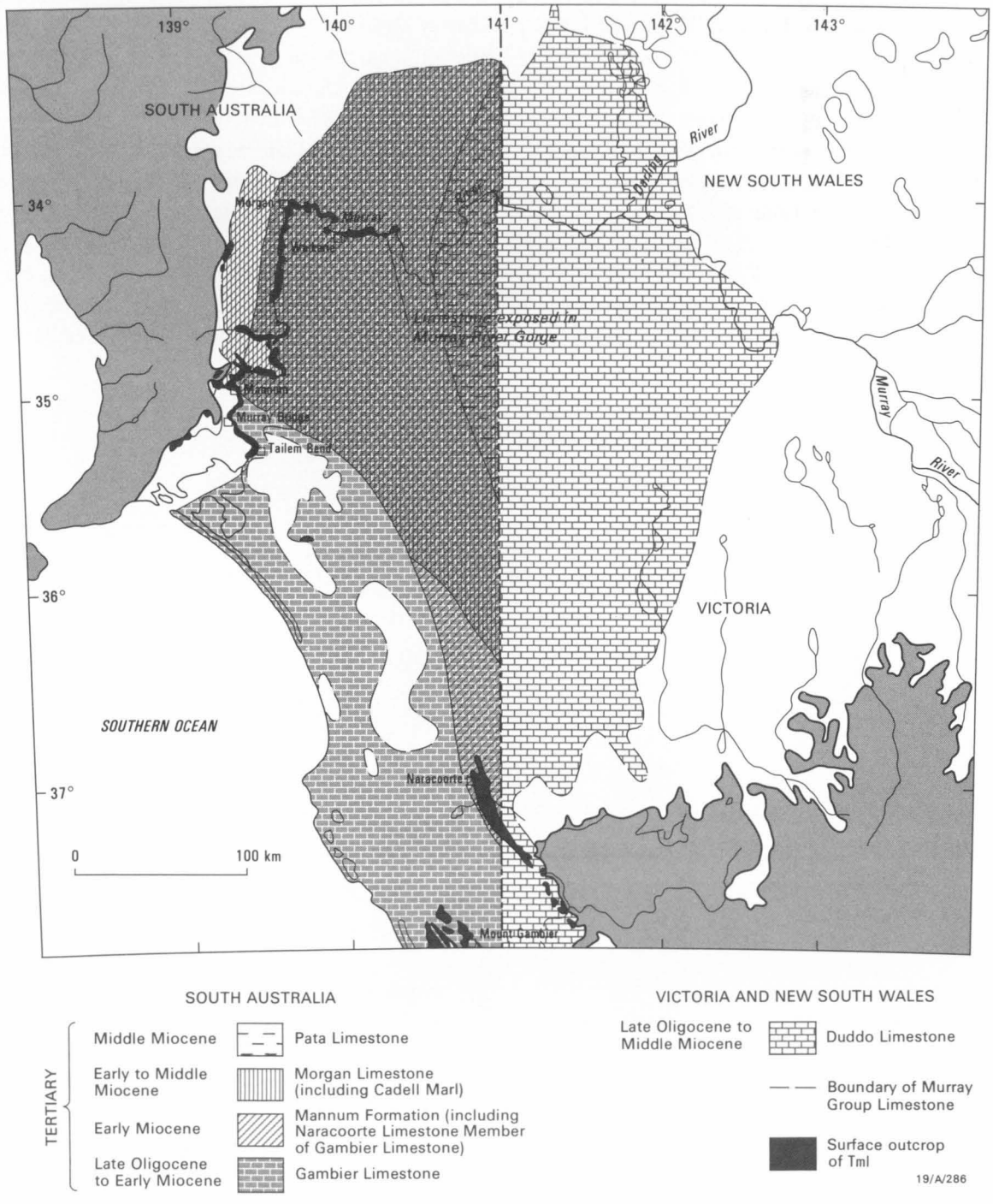


Fig. 63. Distribution and stratigraphic position of limestone formations of the Murray Group — Gambier Limestone, Mannum Formation, Morgan Limestone and Pata Limestone (South Australia) and equivalent Duddo Limestone (Victoria and New South Wales).

mation, was previously placed in the Ettrick Formation.

Data sources. Stratigraphic descriptions of the Ettrick Formation in South Australia are recorded in Ludbrook (1957, 1961a, 1969a). Lawrence (1966, 1975) provided descriptions of Victorian occurrences. The geology and hydrogeological significance of the Ettrick Formation are discussed by Brown (1989) and Brown & Radke (1989). Additional lithologic and palaeontologic descriptions of the formation are contained in Lindsay & Bonnett (1973), and Lindsay & Williams (1977).

Unit: 'Murray Group Limestones'
Age: Limestone units of the Murray Group range in age from Late Oligocene to Middle Miocene
Component units: see Table 14
Map symbol: Tml

Lithology. The Murray Group limestones are lithologically variable and in western areas includes skeletal calcarenite (Fig. 56) and local skeletal sandstone. To the north, east and southeast, calcisiltite, micritic and marly limestone predominates (see Tables 15, 16, 17, 19, 22, 23 for lithologic descriptions of individual units). Clay of the Finniss Clay (Table 18) and calcareous clay of the Cadell Marl Lens of the Morgan Limestone (Table 20) occur within the limestone sequence.

Distribution and thickness. The Murray Group limestones extend over a wide area of the western Murray Basin (Fig. 63); they attain a maximum thickness of some 150 m over depocentres, such as the Renmark Trough, and are more than 100 m thick over much of their area of occurrence (Brown & Stephenson, 1986; Plate 12). In the Buccleuch Embayment (Fig. 55), the Murray Group limestones were partly eroded during a Pleistocene marine transgression, and the Group is much thinner in this area. In the Gambier Embayment (Fig. 64), up to 250 m of Gambier Limestone are preserved (O'Driscoll, 1960; Kenley, 1971), but this embayment

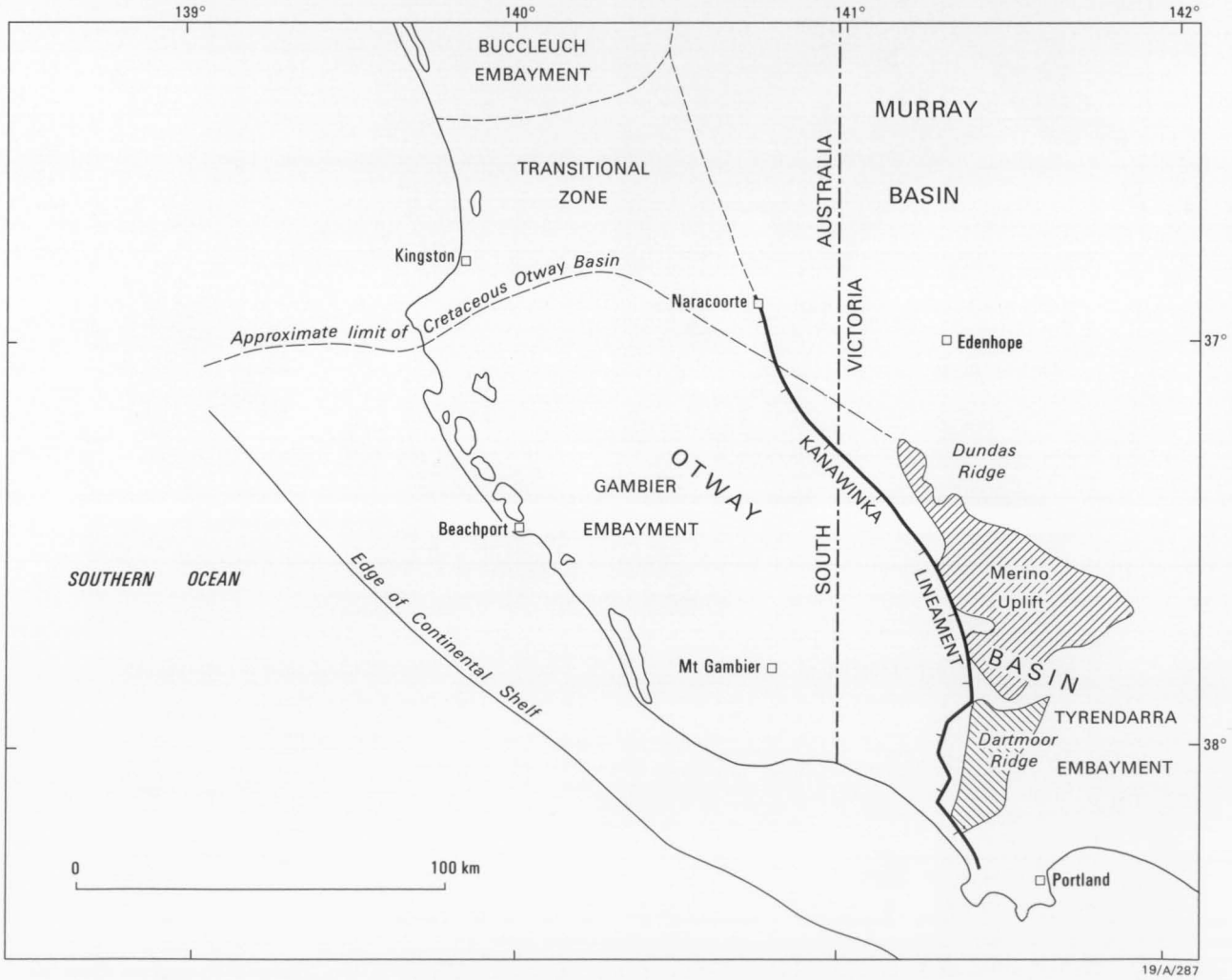


Fig. 64. Location of Gambier Embayment of Otway Basin.

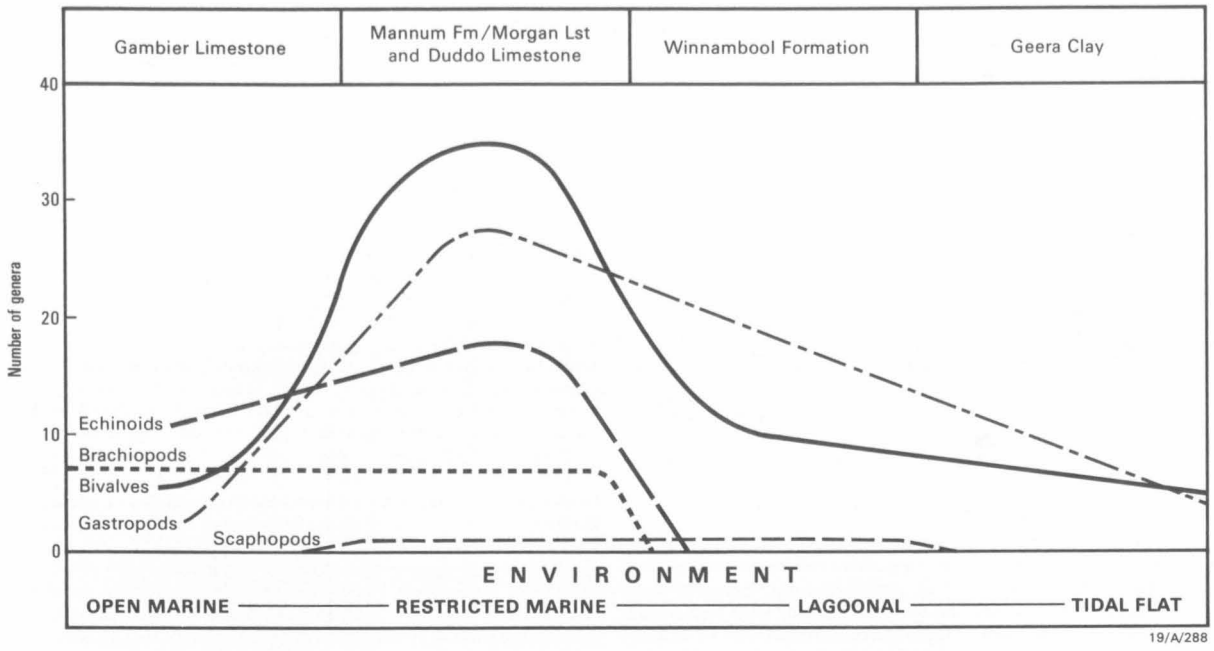


Fig. 65. Relative abundance of various benthic genera in Oligocene–Miocene marine succession of Murray Group (including Gambier Limestone) – see accompanying text for data sources.

is part of the Otway rather than the Murray Basin.

The Murray Group limestones are enveloped to the north and east by calcareous clay of the Winnambool Formation (see palaeofacies diagrams on the enclosed 1:1 000 000 scale map). The boundary between the Murray Group limestones and the calcareous clay of the Winnambool Formation consists of a gradational facies change.

Outcrop, topography, geometry, and structure. Despite increases in thickness over the pre-Cainozoic infrabasins which underlie parts of the western Murray Basin, the Murray Group limestones can be considered to form a horizontal sheet of sediment, which is locally disrupted by faulting (see cross-sections on the accompanying 1:1 000 000 scale geological map). The limestone is largely concealed (Fig. 63), but crops out at the western margin of the basin, where Mannum Formation onlaps Kanmantoo metamorphic basement, and is locally exposed, particularly in creek beds (Thomson & Horowitz, 1962; Thomson, 1969a). The Morgan Limestone and the Mannum Formation are exposed in the cliff walls of the Murray River gorge (Firman, 1972), which was formed during the Pleistocene by river down-cutting (Twidale & others, 1978); the limestone can also be seen in the beds of some tributaries of the Murray River: in particular the Marne River and Burra Creek (Thomson, 1969a; Firman, 1972; Rogers, 1978).

At the southwestern margin of the basin, Gambier Limestone has been exposed on the upthrown (eastern) side of the Kanawinka Fault (Sprigg & others, 1951; Rochow, 1969), and is also exposed onlapping onto granitic basement of the Padthaway Ridge (Rogers, 1980a). In southwestern Victoria, the Duddo Limestone (locally equivalent to the Gambier Limestone) is exposed by the Glenelg River and its tributaries, and in sinkholes (Lawrence & Abele, 1976, 1988).

Palaeontology. The skeletal calcarenite, micritic limestone and calcareous clay of the Murray Group preserve diverse marine faunas, which are detailed separately in the descriptions of the individual units,

TABLE 14. AGE RANGES OF 'MURRAY GROUP LIMESTONE' UNITS

Component unit	*State*	*Age*
Pata Limestone	S.A.	Middle Miocene
Morgan Limestone	S.A.	Early to Mid-Miocene
Cadell Marl Lens of the Morgan Limestone	S.A.	Early Miocene
Finniss Clay	S.A.	Early Miocene
Mannum Formation	S.A.	Early Miocene
Duddo Limestone	Vic., & N.S.W.	Late Oligocene to Middle Miocene
Gambier Limestone*	S.A.,Vic.	Late Oligocene to Early Miocene
Naracoorte Limestone Member of the Gambier Limestone	S.A.	Early Miocene

* age in Murray Basin only; in Otway Basin Gambier Limestone may range in age from Late Eocene to Middle Miocene (Ludbrook, 1971).

TABLE 15. OLIGOCENE – MIOCENE GAMBIER LIMESTONE OF THE MURRAY GROUP

Unit: Gambier Limestone (included in Murray Group in Murray Basin, but part of Glenelg Group in adjacent Otway Basin)

Age: Late Oligocene to Early Miocene in Murray Basin, Late Eocene to Middle Miocene in adjacent Otway Basin

Map symbol: included in Tml

Component member: Naracoorte Limestone Member

Synonyms: Mount Gambier stone, Mount Gambier Limestone

Lithology. Yellowish-brown, white to cream, bryozoal limestone, with fine to coarse quartz grains, abundant calcitic skeletal debris; minor glauconitic calcareous clay, sparse limonitic grains at base. Usually more consolidated, more even-grained, with higher carbonate content, than other Oligo-Miocene limestones of Murray Basin, but still only weakly lithified. Naracoorte Limestone Member (upper member of Gambier Limestone — see separate description) differs texturally from rest of unit, and is rubbly, highly fossiliferous, leached coquinite (Ludbrook, 1961a).

Distribution and thickness. Chiefly occurs in Gambier Embayment of Otway Basin (Fig. 64), but also in SW Murray Basin (marine sedimentation contiguous between both basins from Eocene to Middle Miocene). Exact limits of distribution within Murray Basin not well-defined, owing to distribution of deep boreholes and difficulties in distinguishing between Oligo-Miocene limestones on drillers' logs. Approximate distribution (Fig. 63), based on O'Driscoll (1960), Ludbrook (1961a), and Brown & Stephenson (1986). Known to be present in deeper parts of basin, such as Renmark Trough (O'Driscoll, 1960; Ludbrook, 1963c; Firman, 1972). In Buccleuch Embayment (Fig. 55), distribution of Gambier Limestone is patchy owing to (a) presence of 'islands' of Padthaway Ridge granites at time of deposition, and (b) Pleistocene erosion.

Maximum thickness in Otway Basin — 249 m in County Grey S.A. (O'Driscoll, 1960). Kenley (1971) recorded in excess of 237 m in Nelson bore, SW Victoria. On PENOLA and NARACOORTE, at west margin of Gambier Embayment (Fig. 64), Miocene part of Gambier Limestone sequence eroded during Pleistocene (Ludbrook, 1971), and replaced by reworked calcarenites of Coomandook Formation, and aeolianites of Bridgewater Formation. Gambier Limestone also eroded in Buccleuch Embayment (Fig. 55) during Pleistocene, although remnants survived adjacent to granitic 'islands' of 'Padthaway Archipelago' (Chapman, 1943; Rogers, 1980a). Maximum thickness in Murray Basin not known, although Ludbrook (1963c) gave figure of 38 m in A.O.C. North Renmark No.1.

Geometry and topography. Forms extensive sheet of sediment in west Murray Basin, with slight thickening in deeper parts, over pre-Cainozoic troughs; crops out in Otway Basin, but in Murray Basin only at surface in extreme south, near Naracoorte (Rochow, 1969), and as badly weathered outcrop adjacent to Padthaway Ridge granite on PINNAROO (Chapman, 1943; Rogers, 1980a).

Palaeontology. Richly fossiliferous, but faunally distinct from younger limestones of 'Murravian Gulf' (see Appendix 6) — result of more open-marine conditions during deposition of Gambier Limestone. Macrofossil assemblage (Fig. 66) indicates bryozoa, echinoids, neritic forms dominant, in contrast to molluscan and echinoid assemblage which dominates younger limestones (Figs 69, 72). Microfauna described by Ludbrook (1961a), who noted Gambier Limestone rich in planktonic foraminifera (in contrast to other Oligo-Miocene limestones of Murray Basin).

Age evidence. Dated Late Eocene to Early Miocene, in Gambier Embayment (Fig. 64), on micropalaeontological evidence (figs. 3–5 of Ludbrook, 1971). In Murray Basin proper, Gambier Limestone of Late Oligocene to Early Miocene age; Early Miocene component (Naracoorte Limestone Member) only in far south, where dated by Ludbrook (1961a) using foraminifera; elsewhere in Murray Basin, Gambier Limestone restricted in age to Late Oligocene on grounds of stratigraphic position above Ettrick Formation and below Mannum Formation. In Buccleuch Embayment, overlies Oligocene Compton Conglomerate wherever both units found in same borehole (Brown & Stephenson, 1986), although an outcrop of ?Gambier Limestone on Padthaway Ridge may be as young as Middle Miocene (Rogers, 1980a).

Characteristics. In Murray Basin, distinguished from underlying Ettrick Formation (and/or Compton Conglomerate) on lithology. Differentiating Gambier Limestone from overlying Mannum Formation more difficult — equivalents of both included in Duddo Limestone in N.S.W. and Victoria. Gambier Limestone usually more consolidated, less sandy, than Mannum Formation, but micropalaeontology only sure method of distinguishing between them. In Buccleuch Embayment, Gambier Limestone differentiated from underlying Buccleuch beds (equivalent to Lacepede Formation of Otway Basin) by lithology. Calcarenites of Coomandook and Bridgewater Formations, partly derived from Gambier Limestone in Buccleuch Embayment, but usually sandier, less consolidated, than Gambier Limestone.

Environment of deposition. Gambier Limestone (with possible exception of Naracoorte Limestone Member) is rich in planktonic foraminifera, deposited under open-marine conditions on shallow continental shelf — in contrast with more restricted-circulation shallow-marine conditions under which other Oligo-Miocene limestones of Murray Basin deposited. In comparison with overlying Naracoorte Limestone, Gambier Limestone deposited in cool temperate zone (James & Bone, 1989).

Stratigraphic nomenclature. Named after city of Mount Gambier, S.A. 'Mount Gambier stone' first used by Tenison Woods (1862), later modified to Mount Gambier limestone(s) by that author (1865). 'Gambier Limestone' in common use by middle of this century (Sprigg, 1952a; Ludbrook, 1957); formalised by Ludbrook (1961a, p.28).

Lateral facies changes common within Gambier Limestone; various subdivisions recognised in Otway Basin by different authors (Kenley, 1971, p.112). Ludbrook (1961a) informally described 'upper' and 'lower' members of Gambier Limestone in South Australian Otway Basin, but these not recognised in Murray Basin proper (where only formalized subdivision remains Naracoorte Limestone Member). Gambier Limestone originally part of Glenelg Group of Sprigg & Boutakoff (1953) — whereas Mannum Formation, Morgan and Pata Limestones belong to Murray Group of Ludbrook (1957).

Type section. Type locality selected by Ludbrook (1961a) as sinkhole in public gardens at town hall, Mt Gambier — original section described by Tenison Woods (1860, 1862). Unit nowhere fully exposed; no formal type section in modern sense.

Stratigraphic relationships. Conformable over Ettrick Formation. Disconformable over Compton Conglomerate. Unconformable over, and abuts, Cambro-Ordovician granites of Padthaway Ridge. Locally interfingers with Ettrick and Winnambool Formations. Conformable under Winnambool Formation in north, under Mannum Formation in centre and south. In Buccleuch Embayment, remnants disconformable to unconformable under Coomandook and Bridgewater Formations (see cross-sections C–D, E–F on enclosed 1:1 000 000 geological map).

Correlations. Gambier Limestone known by same name in both Murray and Otway Basins; in west Murray Basin partly facies related to Ettrick Formation, part correlative of non-marine Olney Formation in east and north (Brown, 1985; Brown & Stephenson, 1986); also part correlative of Port Willunga beds of St. Vincent Basin (Ludbrook, 1969a).

Hydrogeology and economic geology. Part of Murray Group aquifer system. Widely used as groundwater source in Gambier and Buccleuch Embayments. Used as building stone in Otway Basin, although outcrops in Murray Basin of insufficient quality for this purpose.

Data sources. Tenison Woods (1860, 1862, 1865, 1867a,b), Chapman (1943), Sprigg (1952a), Sprigg & Boutakoff (1953), Ludbrook (1957, 1961a, 1963c, 1969a, 1971), O'Driscoll (1960), Kenley (1971), Firman (1972), Rogers (1980a), and James & Bone (1989).

TABLE 16. LOWER MIOCENE NARACOORTE LIMESTONE MEMBER OF THE GAMBIER LIMESTONE

Unit: Naracoorte Limestone Member of Gambier Limestone

Age: Early Miocene

Map symbol: included in Tml

Lithology. Highly fossiliferous (in places coquinoid) sandy limestone; rubbly, leached in outcrop (Ludbrook, 1957, 1961a).

Distribution, thickness, and topography. Upper member of Gambier Limestone, restricted in distribution to upthrown (east) side of Kanawinka Fault scarp (NARACOORTE) southeast S.A., where exposed and has subdued geomorphic expression; elsewhere only in subsurface. Rogers (1980a) does not record Naracoorte Limestone in PINNAROO. Included in Duddo Limestone in Victoria. Boundaries poorly defined, but probably grades into Mannum Formation north of Bordertown. Maximum thickness 28 m near Frances, but generally < 10 m (Ludbrook, 1961a).

Palaeontology and age evidence. Ludbrook (1957) regarded macrofauna and microfauna of Naracoorte Limestone Member as not differing markedly from rest of Gambier Limestone. Coquina in places, with abundant casts, moulds of molluscs, echinoids (Ludbrook, 1961a); molluscs dominated by pectens and large gastropods Cypraea dorsata and Alcithoe (Cottonia) heptagonalis (Ludbrook, 1961a). Originally dated Late Oligocene – Early Miocene (Ludbrook, 1957), but later revised to Early Miocene only, based on presence of planktonic foraminifera Globigerinoides triloba (Ludbrook, 1961a). Stratigraphic position at top of Gambier Limestone does not greatly constrain interpretations of age, as Gambier Limestone ranges from Upper Eocene to Middle Miocene in Otway Basin (Ludbrook, 1971; Kenley, 1971), although likely to have an oldest age of Late Oligocene within Murray Basin.

Characteristics. Texturally distinct from more even-grained Gambier Limestone, being rubbly, more highly fossiliferous, although faunas of both units similar (Ludbrook, 1957, 1961a). Easily distinguished from overlying Loxton – Parilla Sands, Molineaux Sand, and (probable) Padthaway Formation on basis of lithology. Can be confused with calcarenite of Bridgewater Formation in borehole logs – but more highly fossiliferous, more coherently cemented, less sandy than that formation.

Environment of deposition. Shallow-water, open-marine environment; most Gambier Limestone deposited in open sea, but high fossil content, and local coquinal nature of Naracoorte Limestone, indicates deposition in relatively shallow water; probably in warmer water than underlying Gambier Limestone (Ludbrook, 1961a).

Stratigraphic nomenclature and type section. Named after town of Naracoorte, S.A. by Ludbrook (1957), who designated north side of quarry near Naracoorte (operated by A. James & Sons) as type section; she later briefly described this quarry (Ludbrook, 1961a), but did not detail its exact location in either publication. Name Naracoorte Limestone not in common use today; not shown on either face or legend of NARACOORTE geological map (Rochow, 1969). Kenley (1971) recognised Naracoorte Limestone as distinct unit, but did not extend it into west Victoria.

Stratigraphic relationships. Recognised only in S.A., where local, upper member of Gambier Limestone – one of few remaining Miocene remnants of latter. Forms transitional unit between (largely eroded) open-marine Miocene limestone of Gambier Embayment and more restricted-marine limestone of Murray Basin proper. Disconformable over older components of Gambier Limestone (Ludbrook, 1957). May grade laterally into Mannum Formation in northeast NARACOORTE, but this relationship is inferred and not proven. Unconformable under Pliocene Loxton – Parilla Sands, Pleistocene Molineaux Sand. West of Kanawinka Fault, inferred but not demonstrated, to be disconformable to unconformable under Pleistocene Bridgewater and Padthaway Formations.

Hydrogeology and economic geology. Lies above modern water table, therefore not an aquifer. High in carbonate content and quarried for lime in past. Used for road screenings (Ludbrook, 1961a).

Data sources. Ludbrook (1957, 1961a, 1971), Kenley (1971), Rogers (1980a), and James & Bone (1989).

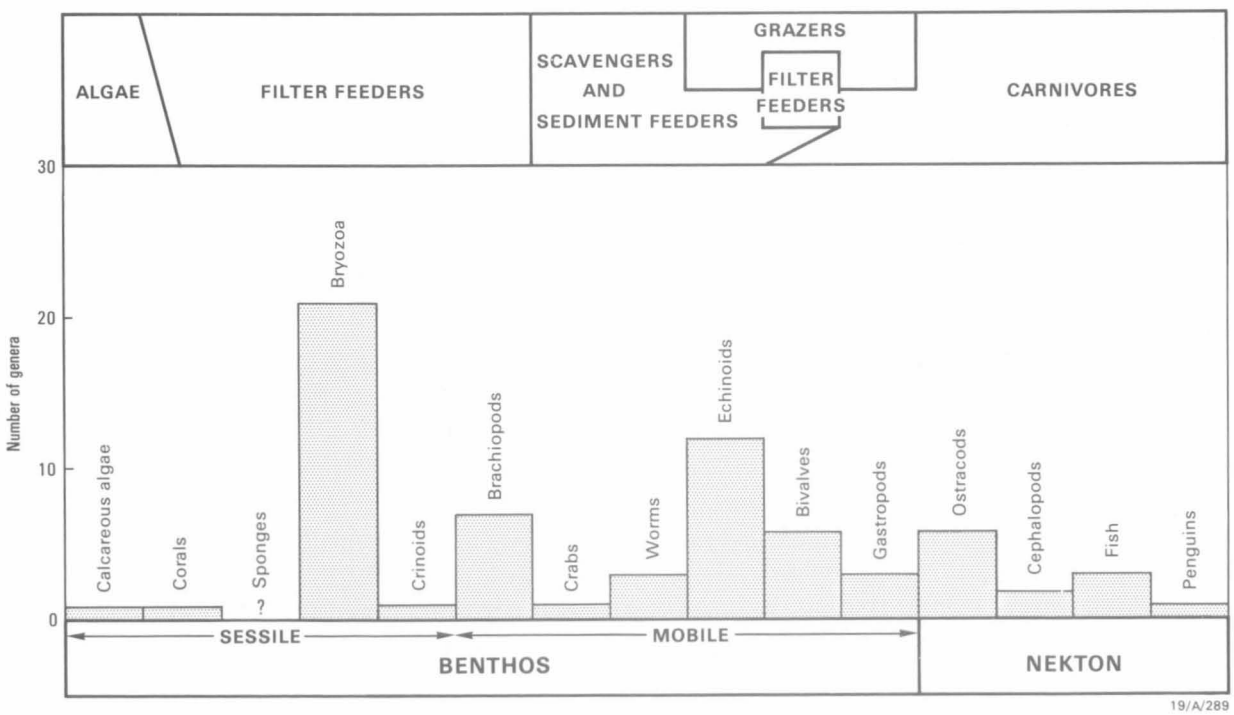


Fig. 66. Macrofauna in Gambier Limestone.

TABLE 17. UPPER OLIGOCENE – LOWER MIOCENE MANNUM FORMATION OF THE MURRAY GROUP

Unit: Mannum Formation of Murray Group

Age: Late Oligocene to Early Miocene (mainly Early Miocene)

Map symbol: included in Tml

Synonyms: Part of informal 'Morgan – Mannum Limestone', 'Murray Group limestones', 'Murray Group calcarenites'

Lithology. Mainly skeletal calcarenite to calcareous sandstone; light cream to yellow-brown; highly fossiliferous; moderately well compacted, partially cemented. Calcareous clay matrix; clay bands, lenticular pockets, in places. Quartz grains rounded to sub-angular, fine to coarse-grained. Calcite mainly in form of skeletal remains, pellets, debris, commonly stained with limonite (Ludbrook, 1961a). Abundant megafossils form coquinoid lenses (Figs 56, 67).

Distribution and thickness. Recognised only in S.A. – equivalents in N.S.W. and Victoria included in Duddo Limestone (Fig. 63). Even within S.A., Mannum Formation difficult to distinguish from overlying Morgan Limestone, and not differentiated in most bores logged by O'Driscoll (1960) or Brown & Stephenson (1986). Combined areal distribution of these two units well known, but relative thicknesses in many locations are not. Mannum Formation type section 20 m thick (Fig. 68; Ludbrook, 1957, 1961a); A.O.C. North Renmark No.1 has 24 m (Ludbrook, 1963c); up to 75 m in bores near Waikerie (Lindsay & Bonnett, 1973); Firman (1972) gave average of 30 m as thickness on RENMARK, but this is probably conservative; in CHOWILLA, Rogers (1978) gave 46 m as thickness of 'Mannum Formation equivalents', but this probably includes elements of Winnambool Formation.

Geometry, internal morphology, and topography. Forms continuous slab of sediment across area of distribution, with slight thickening in central-west, over pre-Cainozoic infrabasins; Ludbrook (1961a) divided Mannum Formation into 'upper' and 'lower' members, based on slight differences in lithology and fauna at type section. Unlike 'members' of Morgan Limestone, however, subdivisions of Mannum Formation not recognised in borehole logs or outcrop elsewhere. Forms part of Murray River cliffs, between North West Bend and Tailem Bend; also exposed in Marne River valley, but otherwise in subsurface.

Palaeontology and age evidence. Rich marine macrofossil fauna (Appendix 6): echinoids, bivalves, gastropods, brachiopods, bryozoa, crinoids, scaphopods, with neritic forms represented by sharks and cephalopods (Fig. 69; Ludbrook, 1961a). Echinoid Lovenia 'forbsei T.Woods' particularly common, forming coquinas in places (Ludbrook, 1957, 1961a). Ludbrook (1961a), Lindsay & Bonnett (1973) described microfauna of Early Miocene age; lowermost part of Mannum Formation may extend back to latest Oligocene (Lindsay & Bonnett, 1973); Early Miocene age consistent with stratigraphic position of Mannum Formation, above Ettrick Formation and Gambier Limestone (both mainly of Late Oligocene age), and below Finniss Clay and Morgan Limestone (both of Early Miocene age). Latest Oligocene age, reported by Lindsay & Bonnett (1973), may reflect diachronous nature of boundary between Ettrick and Mannum Formations – this date, however, depends upon those workers' interpretation of a problematical "pale-brownish-grey marly glauconitic limestone" encountered in bores at Waikerie, originally named Gambier Limestone (Lindsay, 1965b), but later considered to be at base of Mannum Formation (Lindsay & Bonnett, 1973).

Characteristics. Distinguished from other limestones of Murray Group mainly on palaeontological grounds, and to lesser extent lithology (Ludbrook, 1957, 1961a). Recognised as separate formation only in S.A., and even in that State, seldom distinguished from Morgan Limestone in bore logs (O'Driscoll, 1960). Contains sparser macrofauna than Morgan Limestone (Figs 69, 72), and has distinctive microfossil assemblage (Ludbrook, 1961a). Because of lower fossil detritus content, Mannum Formation has higher proportion of quartz, and lower proportion of carbonate, than Morgan Limestone. Higher clay content than Gambier Limestone. Shallow-marine to littoral fossil assemblage, whereas that of Gambier Limestone more indicative of open sea (Ludbrook, 1961a).

Environment of deposition. Deposited in Oligo-Miocene 'Murravian Gulf' over large part of west Murray Basin; Ludbrook (1961a) regarded fauna as shallow-marine to littoral, and described gradual submergence of a granite island near Mannum – indicates deposition during transgressive phase of marine sedimentation in Late Oligocene – Early Miocene. Firman (1972) recorded Mannum Formation transgressive over Kanmantoo bedrock at west margins of Murray Basin.

Stratigraphic nomenclature and type section. Named after town of Mannum, County Sturt, S.A. Type section designated by Ludbrook (1957) as exposure at Mannum Pumping Station (Figs 56, 67, 68); section incomplete as base not exposed. Since first described by Ludbrook, section reduced by construction work at pumping station; total thickness of 19 m (Ludbrook, 1961a), split into lower member of 8 m and upper member of 11 m – separated by irregular contact, and differ slightly in lithology, palaeontology.

Stratigraphic relationships. Conformable over Gambier Limestone or Ettrick Formation. Unconformable over Kanmantoo basement rocks near west margin of basin (Ludbrook, 1957, 1961a; Firman, 1972). In some bores to north and east, Murray Group limestone formations interfinger with, and are both underlain and overlain by, Winnambool Formation (Brown & Stephenson, 1986). Likely that limestone north of Murray River (CHOWILLA and BURRA) includes both Mannum Formation and Morgan Limestone. Mannum Formation conformable under Finniss Clay and Morgan Limestone, although Ludbrook (1957) recorded diastem between Mannum Formation and Finniss Clay at type section (Fig. 68).

Correlations. Part correlative of Duddo Limestone in N.S.W. and Victoria. Lowermost part of Mannum Formation time correlative of uppermost Gambier Limestone and Naracoorte Limestone. Facies equivalent of Winnambool Formation and Geera Clay (Fig. 45).

Hydrogeology and economic geology. Part of lower Murray Group aquifer system. Used mainly for town water supplies, in contrast to upper part which is used mainly for agricultural purposes (Barnett, 1983). Quarried as building stone in past, particularly at Murray Bridge and Mannum (Ludbrook, 1961a). Used as road aggregate in SW.

Data sources. Ludbrook (1957, 1961a, 1963c), O'Driscoll (1960), Lindsay (1965b), Firman (1972), Lindsay & Bonnett (1973), Rogers (1978).

and in Appendix 6. The macrofauna and microfauna in Victoria were first described by Chapman & Gabriel (1914) and Chapman (1916, 1936), and further microfaunal listings are recorded in Crespin (1946, 1947) and Abele (1970). In South Australia, Ludbrook (1957, 1961a, 1963a) studied both the macrofossils and the foraminifera of the western Murray Basin. Additional listings are to be found in a series of reports by Lindsay & Bonnett (1973), Lindsay & Giles (1973), Lindsay & Williams (1977), and Lindsay (1985a), as well as in numerous unpublished reports produced by the South Australian Department of Mines and Energy. Several workers have reported on the microfauna found in petroleum exploration wells and bores (these reports are listed in Appendix 4). The Miocene to Pleistocene marine macrofaunas of the Murray Basin were assigned to the Southeastern Australian Faunal Province by Darragh (1985), whose work was based on molluscs.

The dominant macrofossils of the skeletal limestone of the Murray Group are bryozoans, molluscs, and echinoderms, with brachiopods, corals,

Fig. 67. Skeletal calcarenite of Oligocene–Miocene Mannum Formation of Murray Group, at Mannum Pumping Station (ADELAIDE).

TABLE 18. LOWER MIOCENE FINNISS CLAY OF THE MURRAY GROUP

Unit: Finniss Clay of Murray Group

Age: Early Miocene

Map symbol: included in Tml

Lithology. Variegated, blue-grey, green, brown plastic clay; poorly lithified; local nodules of radiating gypsum crystals up to 15 cm diameter (Ludbrook, 1961a). Minor presence of fine angular quartz, calcite fragments, and limonite.

Distribution and thickness. Very patchy distribution, only near west margin of Murray Basin – full extent currently unknown, but almost entirely subsurface. Identified only from small proportion of bores on RENMARK and ADELAIDE (O'Driscoll, 1960). Crops out only in small part of Murray River cliffs near Mannum. Up to 15 m thick, but normally thinner, with average 5 m.

Palaeontology and age evidence. Very poor fauna (Ludbrook, 1961a) – no macrofossils recorded, microfauna impoverished. Dated Early Miocene on stratigraphic position between Oligocene–Early Miocene Mannum Formation and Early–Middle Miocene Morgan Limestone. Lindsay & Bonnett (1973) dated facies equivalent of Finniss Clay as Early Miocene, citing presence of foraminifer Sherbornina cuneimarginata Wade.

Characteristics. Lithology, stratigraphic position, and restricted area of distribution.

Environment of deposition. Shallow-marine environment; deposition related to transient change in sea-level, or local influx of clastic sediment.

Stratigraphic nomenclature and type section. Named after Hundred of Finniss, County Sturt, S.A. Type section at Mannum Pumping Station (Ludbrook, 1961a), where 5 m of Finniss Clay exposed (Fig. 68).

Stratigraphic relationships. Minor, very patchy stratigraphic unit within Murray Group limestones. Recognised only in S.A. Overlies Mannum Formation; locally interfingers with, and overlain by, Morgan Limestone.

Hydrogeology. Relatively impervious, but, because of patchy distribution, not an effective aquitard within Murray Group aquifer system.

Remarks. Very localised unit not correlated with any other deposit in Murray Basin; Ludbrook (1961a, p.41) records: "Finniss Clay succeeds Mannum Formation with a pronounced lithological change after a cessation of deposition thought to indicate a diastem rather than a disconformity". Thin calcrete at top of Mannum Formation, in places, may be old pedogenic surface, submarine surface, or groundwater precipitate – reflecting availability of calcium carbonate from underlying limestone, in contrast with deficiency in Finniss Clay (Ludbrook, 1961a); diastem, and subsequent deposition of Finniss Clay, possibly related to temporary fall in global relative sea-level around 19 Ma (cf. Vail & others, 1977). Alternatively, localised distribution of Finniss Clay near west margin of basin may reflect pulse of clastic sediment influx from ancestral Mt Lofty Ranges, due to local tectonic or climatic event, rather than eustatic fluctuation.

Data sources. O'Driscoll (1960), Ludbrook (1961a), and Lindsay & Bonnett (1973).

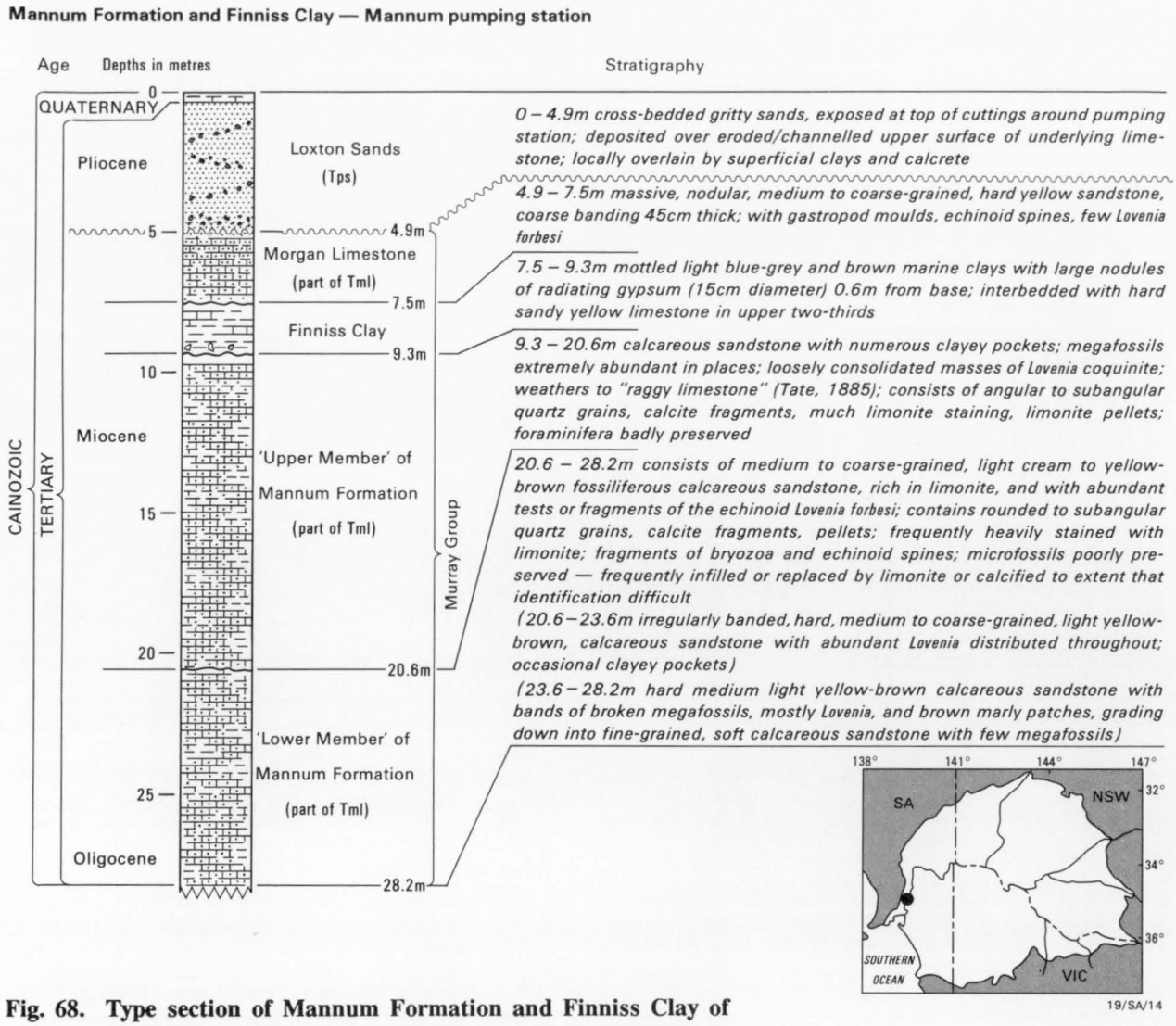


Fig. 68. Type section of Mannum Formation and Finniss Clay of Murray Group, exposed in excavated site of Mannum Pumping Station, South Australia (data extracted from text description of Ludbrook, 1961a, p. 40–52).

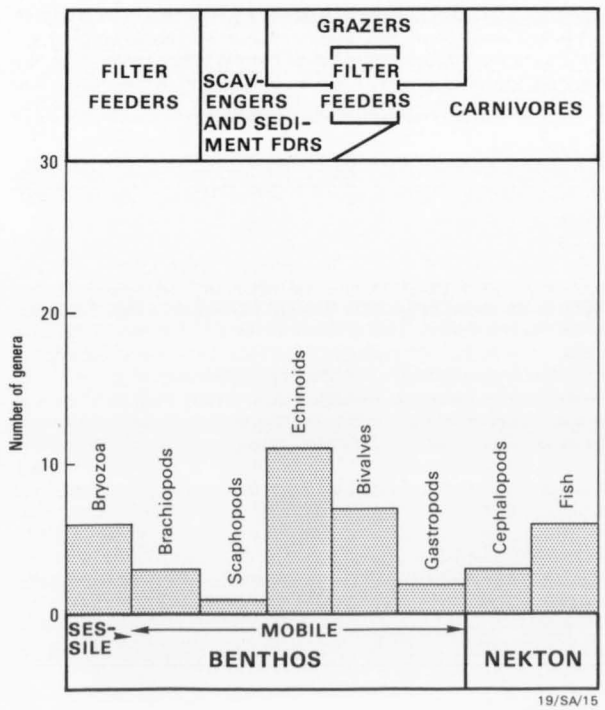


Fig. 69. Macrofauna of Mannum Formation.

TABLE 19. LOWER TO MIDDLE MIOCENE MORGAN LIMESTONE OF THE MURRAY GROUP

Unit: Morgan Limestone of Murray Group

Age: Early to Middle Miocene

Map symbol: included in Tml

Component units: 'Upper Morgan Limestone', Cadell Marl Lens (Table 20), 'Lower Morgan Limestone'

Synonyms: part of informal 'Morgan – Mannum Limestone', 'Murray Group limestones', 'Murray Group calcarenites'

Lithology. Skeletal and quartzose calcarenite, calcareous clay; minor calcareous sandstone. Well cemented, rather than well compacted; clay relatively poorly consolidated. Quartz particles range in size from silt to fine-grained sand; minor glauconite. Considerable facies variation with geographic location. Local calcareous clay lenses (most widespread is Cadell Marl Lens, Table 20). North of Murray River becomes progressively finer-grained – grades into calcareous clay of Winnambool Formation towards NW margin of Murray Basin.

Distribution and thickness. Distributed over wide area of west Murray Basin in S.A. (Fig. 63); equivalents in N.S.W. and Victoria, included in Duddo Limestone. Commonly indistinguishable from overlying Pata Limestone and underlying Mannum Formation in bore logs, so that ascertaining average thickness difficult. Type section 28 m thick (Fig. 70; Ludbrook, 1957, 1961a); elsewhere on RENMARK 15 m thick (Firman, 1972); Lindsay & Bonnett (1973) give thickness of 25 m at Waikerie; Pata Limestone, Morgan Limestone and Mannum Formation have combined thickness of 25 – 140 m on PINNAROO (Rogers, 1980a); combined thickness 80 m on Pinnaroo Block (Brown & Stephenson, 1986), with similar combined thickness on RENMARK. Unlikely Morgan Limestone component greater than 20 – 30 m thick on Pinnaroo Block. West of Pinnaroo Block, Morgan Limestone eroded away in Early Pleistocene, during brief marine transgression, which formed Marmon Jabuk Scarp. Ludbrook (1961a, fig. 35) showed Morgan Limestone in northeast NARACOORTE (Fig. 63), although Rochow (1969) does not mention Morgan Limestone in legend for that map.

Geometry, internal morphology, and topography. Thin, but continuous, band of sediment at, or near top, of Murray Group limestones. To north and east, grades laterally into calcareous clay of Winnambool Formation, whereas in south (most of NARACOORTE) appears not to have been deposited. Internally, Morgan Limestone divided into: (1) lower calcarenitic limestone, (2) calcareous clay to clayey calcarenite (includes Cadell Marl Lens and equivalents), (3) relatively thin upper calcarenitic limestone (Ludbrook, 1961a; Lindsay & Bonnett, 1973; Barnett, 1983); these subdivisions can be traced across wide area. Morgan Limestone forms part of Murray River cliffs in S.A., particularly downstream from Waikerie; elsewhere, outcrops limited to badly weathered occurrences at west margin of basin.

Palaeontology. Abundant, diverse fauna, with bryozoa, echinoids, and molluscs dominant macrofossils (Fig. 72; Appendix 6). Miocene to Pleistocene marine faunas of Murray Basin assigned to Southeast Australian Faunal Province by Darragh (1985) – based on molluscs. During Early Miocene, this faunal province comprised 29% endemic (local) genera, 25% of genera found only in Australian and New Zealand region, 30% of genera found throughout Indo-Pacific region, and only 16% of world-wide genera (Darragh, 1985); likely other faunal groups within Morgan Limestone show similar dominance by endemic and regional taxa. Microfauna described in detail by Ludbrook (1961a), who noted upper (calcarenite) member at type section badly weathered, and has few foraminifera.

Age evidence. Ludbrook (1957, 1961a) used foraminiferal assemblage zones to suggest an Early Miocene age; Lindsay & Bonnett (1973) cited presence of foraminifera Globerinoides transitorius Blow, Globigerinoides falconensis Blow, and Globigerinoides sicanus de Stefani as evidence that uppermost member of Morgan Limestone extended into Middle Miocene. Stratigraphic evidence also suggests Early to Middle Miocene age; underlying Mannum Formation extends into Early Miocene, and overlying Pata Limestone Middle Miocene in age (Ludbrook, 1961a; Lindsay & Bonnett, 1973). Cadell Marl Lens dated latest Early Miocene, consistent with above interpretation.

Characteristics. Without study of fauna nearly impossible to distinguish from underlying Mannum Formation and overlying Pata Limestone on lithology alone in subsurface (O'Driscoll, 1960; Brown & Stephenson, 1986) – in S.A. separated on palaeontological grounds. Where present, Finniss Clay and Cadell Marl Lens provide useful stratigraphic marker horizons.

Environment of deposition. Deposited in 'Murravian Gulf', formed by marine incursion into west Murray Basin during Oligocene and Miocene. Sea covered shallow platform, on which carbonate shoals deposited. 'Gulf' connected to Southern Ocean, but partially submerged Padthaway Ridge provided some protection from open ocean. Abundant macrofauna, dominated by filter feeders, suggests shallow-water, high nutrient conditions; degree of dissociation of skeletal debris suggests relatively high-energy sea floor, well within wavebase zone. Ludbrook (1969a) estimated Early Miocene water temperatures about 23°C to 25°C – comparable with those found today in subtropical to tropical latitudes. Ludbrook (1961a) thought uppermost member represented regressive sequence deposited as sea began to retreat from Murray Basin – consistent with other evidence of regression, particularly enveloping of Murray Group limestones by Winnambool Formation and Geera Clay (Brown, 1985) in Middle Miocene (Fig. 45).

Stratigraphic nomenclature. Named by Ludbrook (1957) after Morgan, south of North West Bend on Murray River, County Eyre (RENMARK).

Type section. Type section for both Morgan Limestone and Cadell Marl Lens selected by Ludbrook (1957) in Murray River cliffs 6.5 km south of Morgan (Fig. 70). Described in greater detail by Ludbrook (1961a) – more than 28 m thick, with over 14 m of 'lower' member Morgan Limestone, under 7 m Cadell Marl Lens, under 7 m 'upper' member Morgan Limestone. Exposure of 'lower' member Morgan Limestone varies with fluctuations in level of water in Murray River. Section first examined by Tate (1885), and is type locality for many of his molluscan species.

Stratigraphic relationships. Conformable over Mannum Formation over most of its occurrence. Interfingers with, and overlies, Finniss Clay where that unit is present. On ADELAIDE, locally disconformable over Ettrick Formation (some records of 'Ettrick' may be Winnambool Formation, which interfingers with and grades into Morgan Limestone on CHOWILLA). At NW margin of basin, O'Driscoll (1960) records 'Morgan – Mannum' limestone directly overlying Renmark Group in one bore log, and unconformable over (Kanmantoo) basement in another. Cadell Marl Lens (see Table 20) entirely enclosed by Morgan Limestone. Poorly exposed Pata Limestone conformable over Morgan Limestone where former present (Fig. 63). North of Murray River, Winnambool Formation generally separates Morgan Limestone from Geera Clay. Upper Miocene Bookpurnong beds, Pliocene Loxton – Parilla Sands, and Norwest Bend Formation, all disconformable over Morgan Limestone in places (Fig. 71). In far SW of Murray Basin, possible that Early Pleistocene Coomandook Formation (mainly deposited on Ettrick Formation, Gambier Limestone, and Mannum Formation) unconformable over remnants of Morgan Limestone, although this relationship yet to be observed.

Hydrogeology and economic geology. Part of Murray Group aquifer system (see 'Groundwater'). Locally used as building stone, although thickness of overburden and variability of texture limit exploitation. Quarried and sawn for building stone on small scale at Overland Corner, near Kingston – on – Murray (Ludbrook, 1961a).

Data sources. Tate (1885), Ludbrook (1957, 1961a, 1969a), O'Driscoll (1960), Firman (1972), Lindsay & Bonnett (1973), and Rogers (1980a).

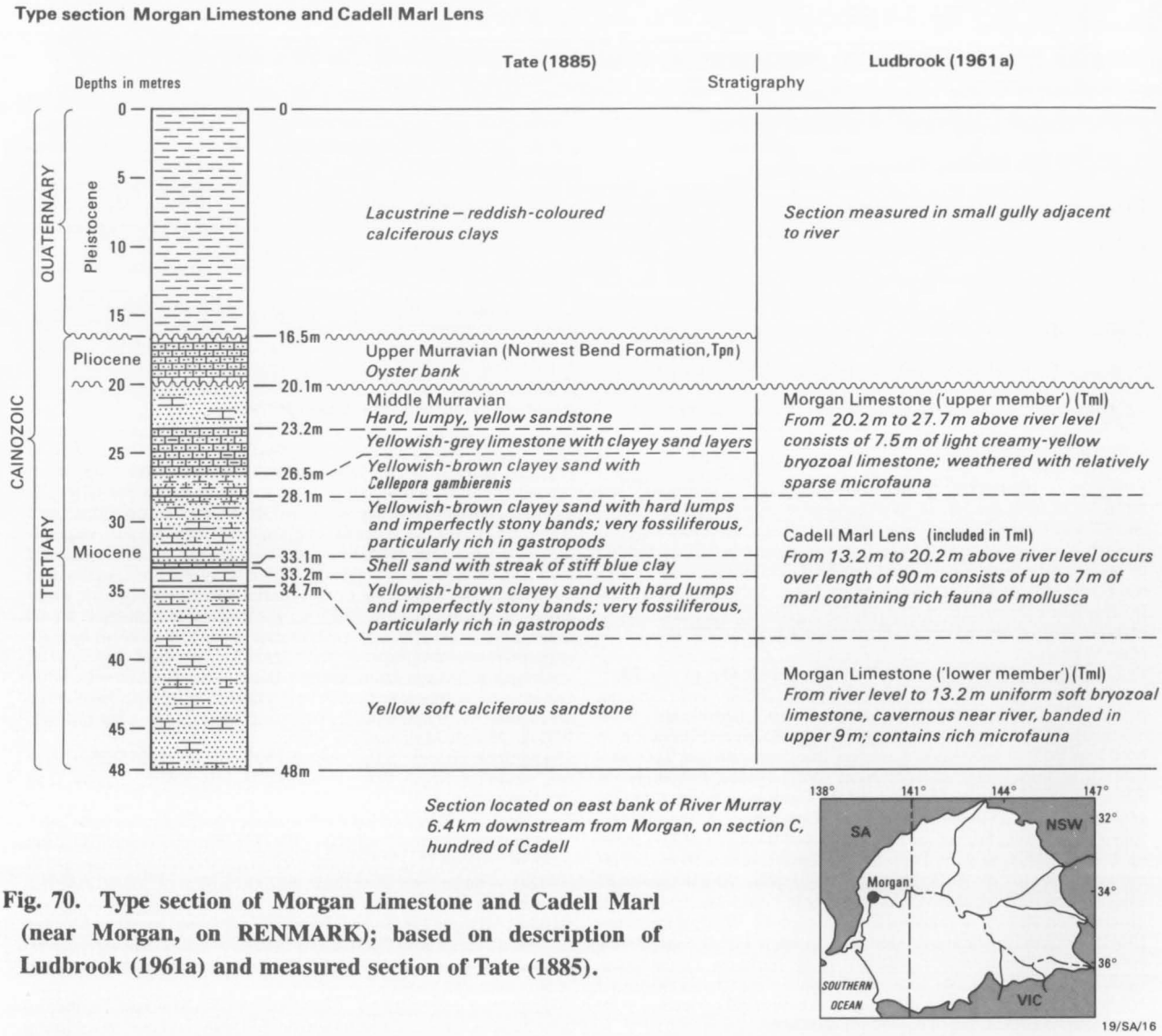


Fig. 70. Type section of Morgan Limestone and Cadell Marl (near Morgan, on RENMARK); based on description of Ludbrook (1961a) and measured section of Tate (1885).

cephalopods, and sharks teeth also common; the microfauna is dominated by foraminifera and ostracods. Individual limestone formations of the Murray Group have differing faunal assemblages (see Figs 66, 69, 72, 74, 76), but these differences are small compared with those between the limestone and the calcareous clay of the Winnambool Formation, and the tidal-flat mud of the Geera Clay (Fig. 65); the Oligo-Miocene faunas of the Murray Basin were highly dependant upon sedimentary facies.

Age evidence. The Murray Group limestones ranges in age from Late Oligocene to Middle Miocene (see above), with most skeletal calcarenite sedimentation taking place in the Early Miocene. Age evidence is both micropalaeontological and stratigraphic (detailed for individual limestone stratigraphic units within the Murray Group in the accompanying Tables 15–20, 22, 23).

Characteristics. The skeletal limestone of the Murray Group is characterised by lithology, and can be readily distinguished using this parameter alone from the calcareous clay of the Ettrick Formation, Winnambool Formation, and Bookpurnong beds, as well as from the clay of the Compton Conglomerate and Geera Clay, and from the sand of the Renmark Group and Loxton–Parilla Sands. The stratigraphic and geographic positions of the Murray Group limestones, together with their palaeontology, are characteristics which distinguish them from the calcarenite of Buccleuch Bed A, the Norwest Bend Formation, and the Bridgewater Formation.

In the Buccleuch Embayment (Fig. 55), the Early Pleistocene Coomandook Formation is composed largely of reworked Murray Group material, and thus is difficult to distinguish from its parent rock in borehole logs. In this case, geographic location, sand content, and the degree of abrasion of skeletal material act as guides: the Coomandook Formation is sandier and its fossils were heavily abraded during reworking and redeposition.

Environment of deposition. The Murray Group

TABLE 20. LOWER MIOCENE CADELL MARL LENS OF THE MORGAN LIMESTONE

Unit: Cadell Marl Lens of Morgan Limestone

Age: Early Miocene

Map symbol: included in Tml

Synonym: Cadell Marl, Cadell Equivalent,

'Gastropod Bed of Middle Murravian Series'

Lithology. Predominantly calcareous clay, locally sandy, grades into clayey limestone; considerable skeletal debris; ranges from pale-grey through blue-grey to cream, brown.

Distribution and thickness. Near west margin of Murray Basin in S.A. – probably extends into NW corner of Victoria, as Lawrence (1966) recorded similar unit in Vic.D.M. Olney No.1. May be contiguous with calcareous clay of Winnambool Formation on central CHOWILLA (see 'Remarks') – for this reason, distribution and thickness difficult to define, but known to occur on ADELAIDE, RENMARK, south CHOWILLA, and possibly BURRA. Type section 7 m thick (Fig. 70; Ludbrook, 1957); in boreholes near Waikerie Lindsay & Bonnett (1973) recorded 9 m, possibly equivalent to Cadell Marl. Firman (1972, p.16) recorded Cadell Marl Lens as "36 m thick by 275 m long in type section", although Ludbrook's (1957, 1961a) descriptions indicate average thickness of 5–10 m, south of Murray River. Exposed only in cliffs of Murray River (Fig. 73), near North West Bend.

Palaeontology and age evidence. Richly fossiliferous, with macrofauna dominated by molluscs. Literature records 17 genera of bivalves, 11 of gastropods, 2 of scaphopods, 7 of sharks teeth (see Appendix 6). Bryozoal fragments common, but not taxonomically described. Macrofaunas in Cadell Marl, similar Winnambool Formation and rest of Morgan Limestone (compared in Table 21, Fig. 74). Microfauna of Cadell Marl described by Ludbrook (1961a), and dated Early Miocene. Lindsay & Bonnett (1973) used foraminiferal evidence to date possible Cadell Marl equivalent as late Early Miocene. Stratigraphic position of Cadell Marl (entirely within Morgan Limestone) indicates late Early Miocene to earliest Middle Miocene age. On foraminiferal evidence, seems likely deposition took place in latest Early Miocene, but did not extend into Middle Miocene.

Characteristics. Distinguished from Pata and Morgan Limestones, Mannum Formation, Geera Clay by stratigraphic position within Morgan Limestone, by lithology, by distinctive macrofauna. Very similar to Winnambool Formation – distinguished mainly on geographic location.

Environment of deposition. Deposited in 'Murravian Gulf' – in more marginal-marine environment than calcarenitic units – in restricted-marine platform and lagoonal environments, similar to those in which Winnambool Formation deposited to north and east (Brown, 1985; Brown & Stephenson, 1986), but Cadell Marl may reflect transient drop in global relative sea-level at about 17 Ma.

Stratigraphic nomenclature. Named after township and Hundred of Cadell, County Albert, S.A. (Ludbrook, 1957, 1961a).

Type section. In 1885, Tate measured section in cliffs of Murray River 6.4 km south of Morgan – type locality for several molluscs, and selected by Ludbrook (1957) as type section for both Morgan Limestone and Cadell Marl Lens (Fig. 70). Lithology, palaeontology described by Ludbrook (1961a, p.53–59).

Stratigraphic relationships. As currently defined, forms lens entirely within Morgan Limestone; may prove to be equivalent of Winnambool Formation (see 'Remarks').

Correlations. Correlated with widespread calcareous clay facies within Morgan Limestone, including 'marl and marly limestone' interval in bores at Waikerie (Lindsay & Bonnett, 1973, p.13); this 'Cadell equivalent' recognised in recent SADME bores (Edwards, 1979, 1981a,b, 1982a,b, 1983), where similar to type section of Cadell Marl Lens (S.R. Barnett, S.A.D.M.E., pers.comm., 1983), although type section more clayey and more highly fossiliferous. Calcareous clay near top of Duddo Limestone in Vic.D.M. Olney No.1 correlated with Cadell Marl (Lawrence, 1966).

Hydrogeology. Partial aquitard within Murray Group aquifer system. Barnett (1983) found equivalent of Cadell Marl acts as semi-confining layer, resulting in low values of specific yield for what had been assumed to be an unconfined aquifer in Wanbi and Karte areas (RENMARK) – effectively split Murray Group limestone into upper water-table aquifer utilized by stock windpumps, and deeper semi-confined aquifer penetrated by irrigation and town water supply wells (Barnett, 1983).

Remarks. Widespread and persistent component of Morgan Limestone, thought to have been deposited during minor regression, when shallower marine conditions than was normal during Early–Middle Miocene prevailed over wide area of 'Murravian Gulf'. Restricted marine and lagoonal conditions also environment of deposition of Winnambool Formation – question arises as to whether Cadell Marl is tongue of Winnambool Formation which temporarily regressed SW into main part of 'Gulf'. Lithologies of Cadell Marl and Winnambool Formation similar. Table 21 and Fig. 74 compare their known macrofaunas (both dominated by molluscs), together with that of Morgan Limestone. Macrofaunas within marine sediments of Murray Group typically endemic to their particular palaeoenvironments, but Cadell Marl and Winnambool Formation (Fig. 74), although similar in overall faunal composition, show considerable differences at genus level – only 4 out of 23 genera of bivalves are common to both units; of 28 genera of gastropods only ubiquitous genus Turritella common to both. However, data for Winnambool Formation from locations several hundred km distant from type section of Cadell Marl, so comparisons in Fig. 74 should be treated with caution; suggests Cadell Marl cannot be regarded as being simply tongue of Winnambool Formation. On other hand, Cadell Marl has 17 genera of bivalves, of which 6 are also found in Morgan Limestone proper; for gastropods corresponding figures are 11 and 3 genera. Would thus seem on palaeontological evidence that Cadell Marl deposited in unique environment, closer to open sea than generally more restricted Winnambool Formation.

Data sources. Tate (1885), Ludbrook (1957, 1961a), Lawrence (1966), Lindsay & Bonnett (1973), Edwards (1979, 1981a, 1981b, 1982a, 1982b, 1983), Barnett (1983), and Brown & Stephenson (1986).

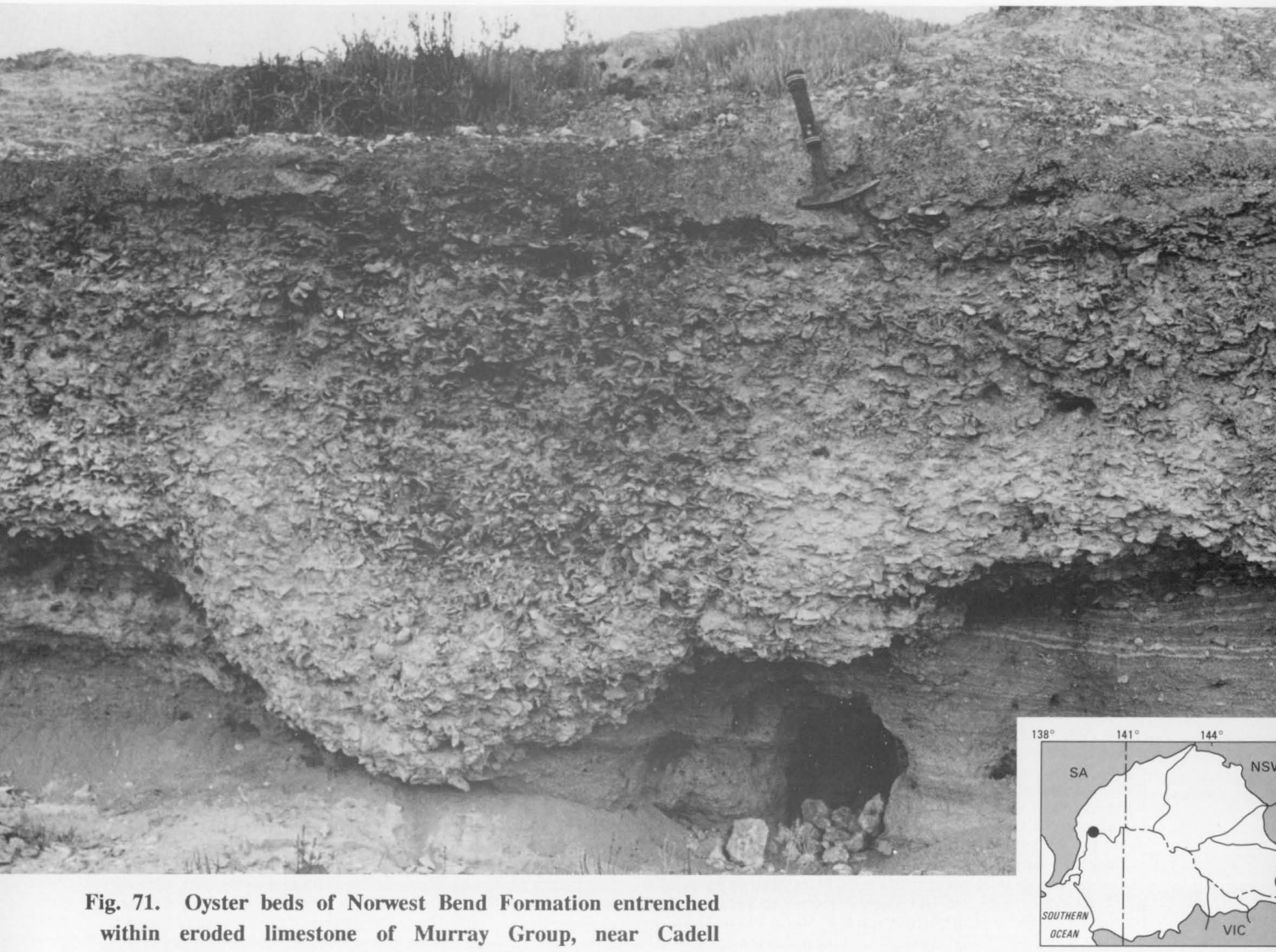


Fig. 71. Oyster beds of Norwest Bend Formation entrenched within eroded limestone of Murray Group, near Cadell (RENMARK).

limestones were deposited in the 'Murravian Gulf', a shallow epicontinental sea which flooded the western Murray Basin from the Late Oligocene to the Middle Miocene.

The Murray Basin has been a low-lying and relatively flat surface of deposition throughout the Cainozoic, and relatively small fluctuations in base-level caused extensive lateral migration of facies boundaries (Brown, 1983, 1985). Throughout the marine transgression, small changes in sea-level led to widespread interfingering between the limestone of the Murray Group and the Winnambool Formation, and between the latter formation and the Geera Clay; the shoreline of the 'Murravian Gulf', as represented by the Olney Formation, also underwent considerable lateral fluctuations. In the west of the basin, the Finniss Clay and Cadell Marl represent similar facies variations caused by minor sea-level falls. Palaeontological and sedimentological data show that slightly different environmental conditions prevailed at different times (see descriptions of individual stratigraphic units). The Pata Limestone represents the last, regressive phase of Middle Miocene limestone deposition.

Stratigraphic relationships. The Murray Group limestones usually overlie the Ettrick Formation, and near the western margin of the Murray Basin, they locally interfinger with that unit. In the Buccleuch Embayment (Fig. 55), the Murray Group limestones may directly overlie the Buccleuch beds, the Compton Conglomerate, or the Renmark Group, but these are local relationships. As mentioned above, the Murray Group limestones also onlap basement near the western margin of the Murray Basin. Near the eastern and northern margin of their area of occurrence, they overlie, interfinger with, and are overlain by their facies equivalent, the calcareous clay of the Winnambool Formation (Fig. 45). The Geera Clay is also a facies equivalent of the limestones, but the two stratigraphic units are only locally in contact.

The Murray Group limestones are disconformably overlain by the Bookpurnong beds, the Loxton–Parilla Sands, and the Norwest Bend For-

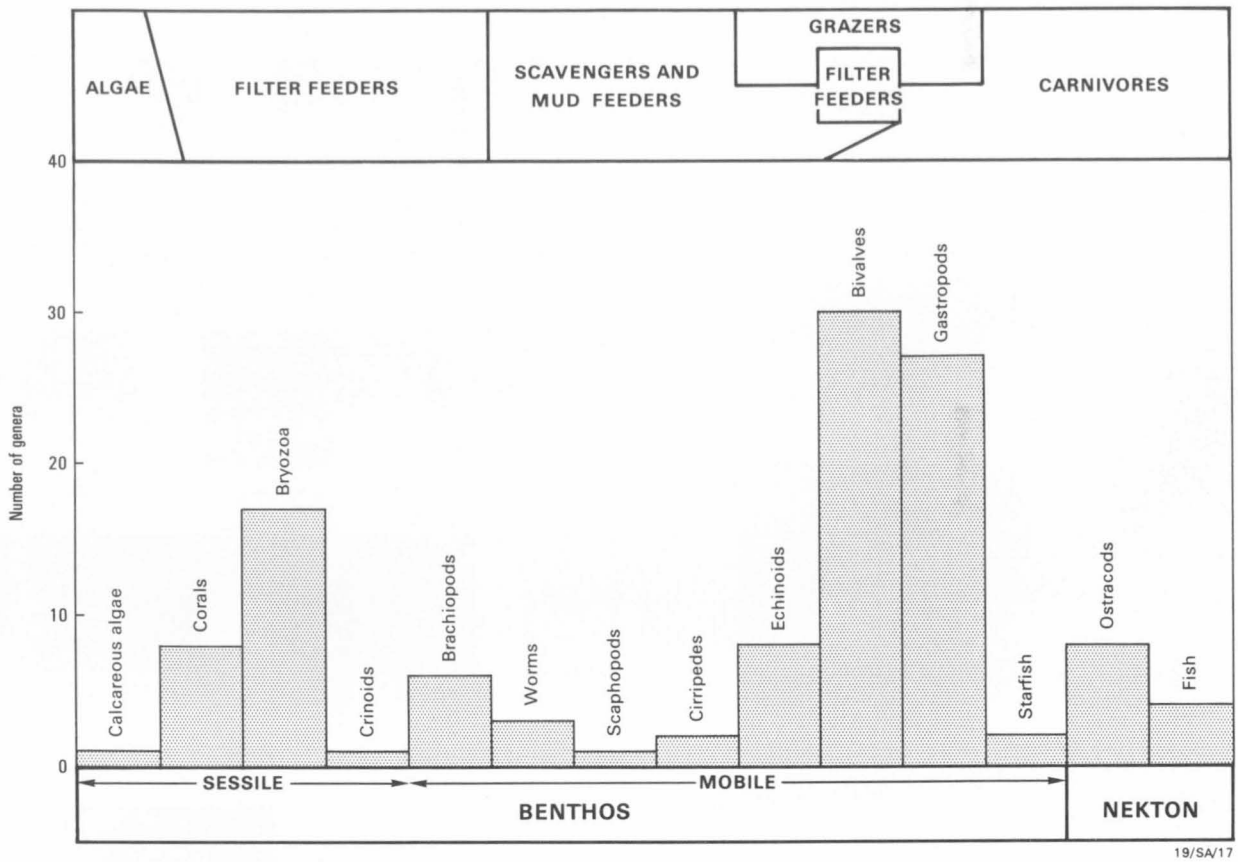


Fig. 72. Macrofauna of Morgan Limestone; only forms identified to genus level are included, but sponges aquatic mammals and terrestrial marsupials have also been recorded.

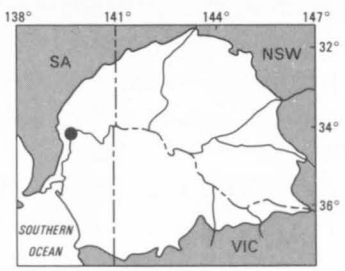


Fig. 73. Cadell Marl exposed in cliffs of Murray River (east bank of river, southeast of Morgan on RENMARK – characterised by abundant presence of gastropods.

TABLE 21. NUMBER OF GENERA OF MACROFOSSIL TYPES IN MORGAN LIMESTONE, CADELL MARL LENS AND WINNAMBOOL FORMATION

Fossil type	*Morgan*	*Cadell*	*Winnambool*
Calcareous Algae	1	0	0
Sponges	0	0	1
Corals	8	0	0
Bryozoa	17	?	1
Crinoids	1	0	0
Brachiopods	6	0	0
Worm traces	3	0	?
Scaphopods	1	2	1
Cirripedes	2	0	0
Echinoids	8	0	0
Starfish	2	0	0
Bivalves	30	17	10
Gastropods	27	11	17
Ostracods	8	0	6
Fish	4	7	0

? signifies fossil type present, but not classified to Genus.
* only one bryozoan Genus identified from Winnambool Formation, but many unclassified forms also present.

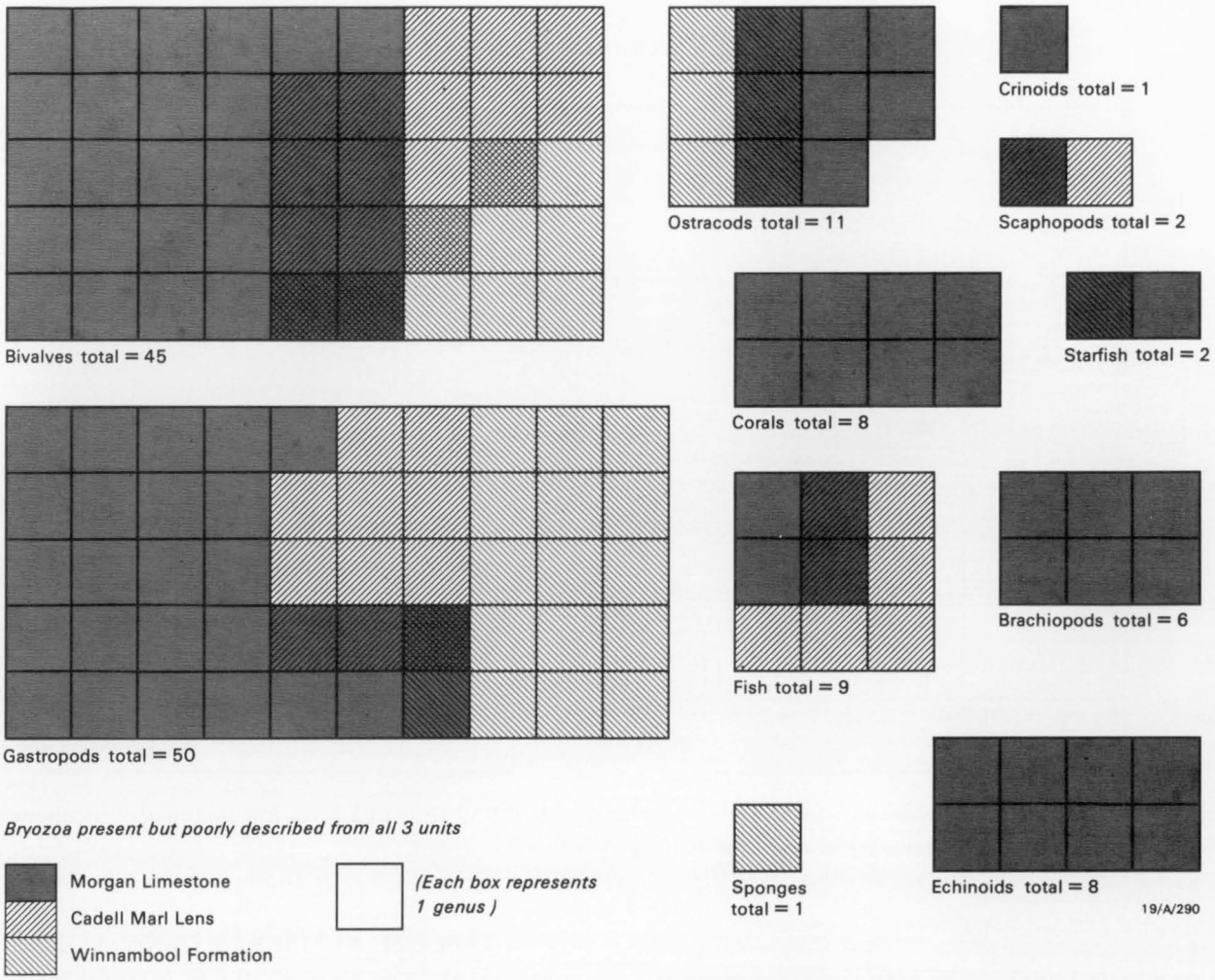


Fig. 74. Distribution and degree of overlap between various fossil genera in Morgan Limestone, Cadell Marl Lens, and Winnambool Formation.

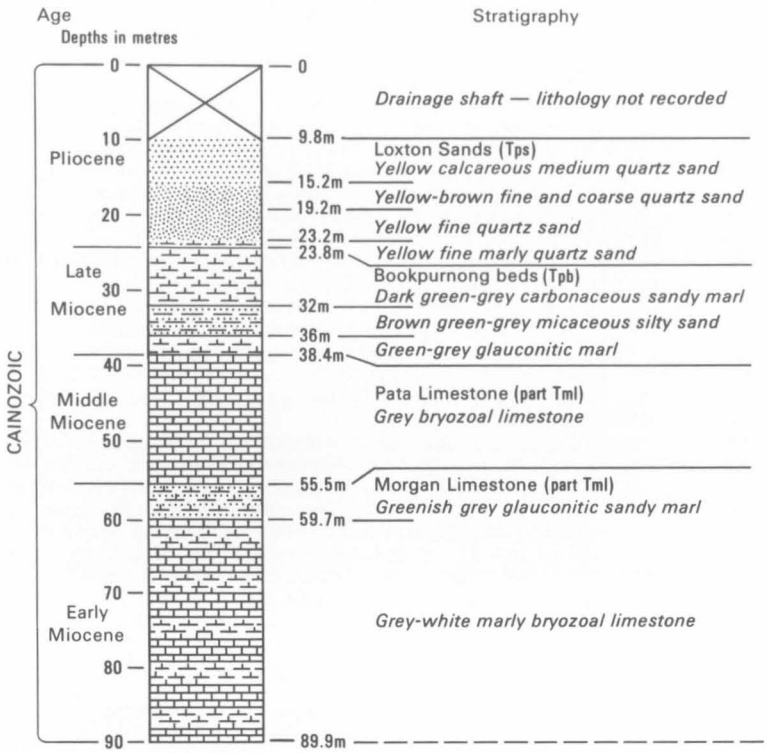
mation. In the Buccleuch Embayment and the Gambier Embayment, the limestones suffered marine erosion during the Pleistocene (O'Driscoll, 1960; Ludbrook, 1961a; Rogers, 1980a), and were partially stripped and reworked, then unconformably overlain by the Coomandook Formation and the Bridgewater Formation. Details of the internal stratigraphic relationships of the Murray Group limestone units are in the descriptions of individual formations given in the accompanying Tables.

Correlations. In the western Otway Basin, the Gambier Limestone extends from the Upper Eocene to the Middle Miocene (Ludbrook, 1971), and is partly equivalent to the Murray Group limestones as a whole in the Murray Basin (Ludbrook, 1969a).

Hydrogeology and economic geology. The Murray Group limestones collectively form one of the major aquifers of the Murray Basin, and the hydrogeology of the unit has been studied by several authors, including Ward (1941, 1946), O'Driscoll (1960), Lawrence (1966, 1975), Reed (1980), and Barnett (1980, 1981a, 1981b, 1983, 1989b). The hydrogeological significance of the Murray Group aquifer system is discussed under 'Groundwater'. The limestones have been locally used both as building stone and road metal (Ludbrook, 1961a).

Data sources. Descriptions of various aspects of the geology of the Murray Group limestones are presented in: Chapman (1916), Ward (1941, 1946), Sprigg & others (1951), Baker (1953), Sprigg & Boutakoff (1953), Ludbrook (1957, 1961a, 1969a, 1971), O'Driscoll (1960), Thomson & Horowitz (1962), Lawrence (1966, 1975), Rochow (1969), Thomson (1969a), Abele (1970), Kenley (1971), Firman (1972), Lindsay & Bonnett (1973), Lawrence & Abele (1976, 1988), Rogers (1978, 1980a), Twidale & others (1978), Barnett (1980, 1981a, 1981b, 1983, 1989b), Reed (1980), Brown (1985, 1989), Brown &

Drainage Shaft 18. Loxton — Section 377, Hundred of Gordon



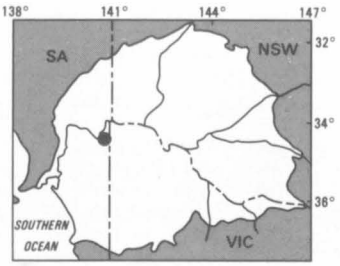


Fig. 75. Standard subsurface type section of Pata Limestone and Bookpurnong beds; Drainage Shaft No. 18, Loxton – Section 377, Hundred of Gordon (after fig. 27, p. 66 of Ludbrook, 1961a).

9.8 – 23.8m — Loxton Sands

9.8–15.2m yellow calcareous medium sand with subangular to subrounded quartz grains, fairly well polished, muscovite, shell fragments and few poorly preserved foraminifera

15.2–19.2m yellow-brown calcareous fine and coarse quartz sand with subrounded polished quartz grains, muscovite, Balanus sp., and few small foraminifera

19.2–23.2m yellow calcareous fine sand with fine angular quartz grains and coarse subrounded polished grains, muscovite, biotite, small foraminifera, including Elphidium pseudonodosum and Elphidium macellum, and ostracods

23.2–23.8m yellow fine micaceous marly sand with fine angular quartz grains, abundant small muscovite flakes, ostracods, mollusca including Syrnola (Evelynella) adelaidensis, and foraminifera with Flintina intermedia, Elphidium advenum, E. pseudonodosum and E. macellum

23.8 – 38.4m — Bookpurnong beds

23.8–32m dark green-grey carbonaceous sandy marl with glauconite and muscovite; abundant microfauna dominated by Flintina intermedia, Elphidium pseudonodosum, lagenids and miliolids; molluscs include Leiopyrga quadricingulata, Placamen subroborata, Tawera dictua; Balanus also present

32–36m brownish green-grey micaceous silty sand and grit; washed residues consist of light reddish brown fine angular calcite fragments and coarse subrounded both clear and milky quartz grains conspicuously ironstained; Leiopyrga quadricingulata and other mollusca present; numerous foraminifera dominated by Bolivina spp. and lagenids

36–38.4m greenish grey highly fossiliferous sandy glauconitic marl; washed residues consist mainly of abundant dark green and brown glauconite, calcite, fine angular quartz grains, limonite, and numerous ostracods; foraminifera as above, but also Operculina victoriensis and Marginopora vertebralis (?reworked); mollusca include Nuculana sp. nov., Turritella sp., and Dentalium (Laevidentalium) sp.

38.4 – 55.5m — Pata Limestone

38.4–45.7m grey-white partially recrystallised limestone with abundant large flat Operculina (?victoriensis), Cibicides victoriensis, Marginopora vertebralis together with Ditrupa spp. fish otoliths, Nuculana sp. nov., Turritella sp., Limopsis sp., Carditidae and Nuculidae

45.7–50.3m pale grey marly bryozoal limestone with numerous Operculina and Cibicides victoriensis and Ditrupa; mollusca (Nuculana and Carditidae) and crustacea present

50.3–55.5m pale grey marly bryozoal limestone with some glauconite; microfauna characterised by numerous Operculina victoriensis and Cibicides victoriensis, with planktonic forms including Orbulina universa, Orbulina suturalis, Globigerinoides bisphaerica, G. triloba and species of Porticulasphaera series; megafauna contains species of Turritella, Dentalium, Nuculana, Limopsis and Carditidae

19/SA/18

TABLE 22. MIDDLE MIOCENE PATA LIMESTONE OF THE MURRAY GROUP

Unit: Pata Limestone of Murray Group

Age: Middle Miocene

Map symbol: included in Tml

Lithology. Bryozoal limestone, typically pale-grey, partially recrystallized, large proportion of skeletal fragments, locally considerable calcareous clay, hard bands with abundant trace fossils of worms such as Ditrupa (Ludbrook, 1961a). As in the underlying Morgan Limestone, Pata Limestone increases in calcareous clay component towards north.

Distribution and thickness. Difficult to ascertain distribution and thickness, because distinguished from Morgan Limestone only by palaeontological evidence, and not recognised in outcrop until recently (S.R. Barnett, S.A.D.M.E., pers. comm., 1983). Not differentiated in N.S.W. or Victoria, so distribution on Fig. 63 (from O'Driscoll, 1960, fig. 16; Ludbrook, 1961a, fig. 36) incomplete. Not differentiated from Morgan Limestone on borehole logs (Brown & Stephenson, 1986). Largely absent from Pinnaroo Block, possibly because of later erosion associated with uplift of that block. Thickness of 17 m in subsurface type section (Fig. 75), but average thickness unknown; Firman (1972) gives "about 15 m" average thickness on RENMARK. Rogers (1980a) records 'fossiliferous clays equivalent to Pata Limestone' in bores at Chowilla dam site, although these may be referred to the Winnambool Formation.

Palaeontology and age evidence. Macrofauna of Pata Limestone not thoroughly described, although Ludbrook (1961a) noted presence of bivalves, gastropods, scaphopods, crustaceans, and worms. She also described microfauna (Ludbrook, 1957, 1961a), and assigned Middle Miocene age on foraminiferal evidence. Stratigraphic position above Early–Middle Miocene Morgan Limestone, and below late ?Middle Miocene–early Late Miocene disconformity (see 'Cainozoic Sedimentation Patterns'), also suggests Middle Miocene age. Probable from stratigraphic evidence, Pata Limestone was deposited between 13 Ma and 11 Ma, although upper/younger components may have been removed by early Late Miocene erosion.

Characteristics. Distinguished from Morgan Limestone only on palaeontological grounds, as lithologically very similar.

Environment of deposition. Deposited in similar environment to that of Morgan Limestone (Table 19), i.e. on shallow, partly protected marine platform. Ludbrook (1961a) noted greenish-grey micaceous, glauconitic, sandy, calcareous clay between the two formations in bore containing Pata Limestone's standard subsurface section (Fig. 75), and took this to represent change in sedimentation. 'Upper' member of Morgan Limestone (Ludbrook, 1961a) marks beginning of Middle Miocene regression which saw sea retreat from west Murray Basin; Pata Limestone deposited as that regression gathered pace, and represents last phase of limestone sedimentation in Oligo-Miocene 'Murravian Gulf'. Grades into Winnambool Formation to north and east; boundary between two formations diachronous and moved southwards in later part of Middle Miocene. Pata Limestone found only near depocentre of Murray Basin – absence of Pata Limestone over much of Pinnaroo Block may be due either to non-deposition or later erosion – some evidence is present that overlying Upper Miocene to Lower Pliocene Bookpurnong beds onlapped partly eroded Pinnaroo Block.

Stratigraphic nomenclature. Named after township of Pata south of Loxton (RENMARK) by Ludbrook (1957).

Type section. Standard subsurface section selected by Ludbrook (1961a) – S.A. Engineering and Water Supply Department shaft No.18 Section 377, Hundred of Gordon, County Alfred. Pata Limestone occurs between 38.4–55.5 m; bore also contains standard subsurface section for Bookpurnong beds (Fig. 75; after Ludbrook, 1961a, fig. 27).

Stratigraphic relationships. Conformable over Morgan Limestone. Thought to interfinger with Winnambool Formation, and possibly with Geera Clay. Conformable under regressive components of latter two units on CHOWILLA. Disconformable under Bookpurnong beds and Loxton Sands. Pata Limestone and Norwest Bend Formation not known to occur at same location (Figs 63, 100), but latter may disconformably overlie Pata Limestone near Overland Corner.

Hydrogeology and economic geology. Part of Murray Group aquifer system (see 'Groundwater'); north of Murray River, Pata Limestone very clayey and value as groundwater source greatly reduced. Only recently recognised in outcrop and, so far as is known, not used for building stone or road aggregate.

Remarks. Represents last regressive pulse of Miocene limestone deposition in west Murray Basin. Not recognised outside S.A., and included with Morgan Limestone for most practical purposes in that State.

Data sources. Ludbrook (1957, 1961a, 1963a), O'Driscoll (1960), Laws & Heisler (1967), Derrington & Anderson (1970), Firman (1972), and Rogers (1978).

Stephenson (1985, 1986), Darragh (1985) Lindsay (1985a), and James & Bone (1989). Numerous additional descriptions of the unit are recorded in petroleum well completion reports, as well as in unpublished South Australian Department of Mines and Energy reports.

Remarks. As mentioned elsewhere (see 'Murray Group'), the limestones in New South Wales and Victoria have been treated as a single unit (Duddo Limestone; Figs 43, 44), whereas equivalent rocks in South Australia have been subdivided into a number of formations (Figs 42, 45). These differing nomenclatures are partly a result of lithology, and partly a result of perception. In Victoria, the unit is recognised on lithology alone, whereas in South Australia an emphasis on biostratigraphy has allowed sub-division of the unit. Lawrence (1966) pointed out that local disconformities and variations in lithology, which occur within the Oligo-Miocene calcarenite sequence in South Australia, cannot be recognised within the dominantly micritic and marly sequence in Victoria (with the exception of a bed equivalent to the Cadell Marl Lens, which was found in Vic.D.M. Olney No.1 bore). In addition, Ludbrook (1957, 1961a) used microfaunal content as a key criterion when she defined the South Australian rock units; detailed palaeontological work is required on Victorian borehole samples before her formations can be extrapolated across the South Australian border. Even in South Australian boreholes, in the absence of palaeontological control, it is very difficult to differentiate between Pata Limestone, Morgan Limestone, Mannum Formation, and Gambier Limestone (O'Driscoll, 1960; Brown & Stephenson, 1986). For these reasons, the Victorian rather than the South Australian usage has been accepted by workers in New South Wales (Woolley & Williams, 1978).

TABLE 23. OLIGOCENE – MIDDLE MIOCENE DUDDO LIMESTONE OF THE MURRAY GROUP

Unit: Duddo Limestone of Murray Group

Age: Oligocene to Middle Miocene

Map symbol: included in Tml

Lithology. Yellow, white, cream, grey, consolidated, well-bedded, medium to coarse-grained calcisiltite, calcarenite; ranges from calcareous clay (poorly consolidated marl) and bioclastic limestone, through skeletal calcarenite to calcareous cemented quartz sandstone. Abundant skeletal detritus in matrix ranging from silty micrite to medium to coarse quartz sand. Sparry calcite cements composed of crystals of 10–60 microns diameter common (Lawrence, 1966). Some fine clay in thin calcareous beds ranging from calcisiltite to calcilutite. Basal beds commonly have dark-grey chert concretions. Glauconitic calcareous clay common in upper part of formation (Lawrence & Abele, 1976, 1988). In comparison with equivalent skeletal limestone units of Murray Group in S.A., Duddo Limestone appears to be finer-grained, with higher micrite and calcareous clay content.

Distribution and thickness. Occurs over wide area of west Victoria and N.S.W. (Fig. 63); equivalent to combined S.A. Oligo-Miocene limestones of Murray Group (including Gambier Limestone; Ludbrook, 1961a, 1969a; Lawrence & Abele, 1976, 1988; Woolley & Williams, 1978). Commonly attains thickness 100 m in NW Victoria – with known maximum of 127 m in Vic.D.M. Olney No.1. Progressively thins away from main depocentres. Grades into calcareous clay facies of both Winnambool Formation in north and east, and Ettrick Formation in south; boundary with each unit diachronous.

Geometry, structure, and geomorphic expression. Thickest over pre-Cainozoic infrabasins under parts of west Murray Basin, but can be considered as horizontal sheet of sediment locally disrupted by faulting. Unlike equivalent limestone formations in S.A., does not crop out in Murray River valley, and almost entirely concealed – equivalents exposed in small area in extreme south of Murray Basin east of Naracoorte, in HORSHAM and HAMILTON, where equivalent to Naracoorte Limestone Member of Gambier Limestone in S.A.

Palaeontology. Diverse marine fauna (Fig. 76). Macrofauna (Appendix 6) first described by Chapman (1916). S.A. data from Ludbrook (1957, 1961a) extrapolated and included in Fig. 76. Bryozoans ubiquitous, with molluscs, brachiopods, echinoids common to abundant (Fig. 65); other macrofossils include corals, crinoids, algae, cephalopods, scaphopods, sharks teeth. Worm burrows and other trace fossils common; microfauna dominated by foraminifera, ostracods (Abele, 1970). Marked change in composition and decrease in diversity of fauna, where Duddo Limestone grades into partly enveloping Winnambool Formation (relationship between facies and fauna in Miocene marine sequence of Murray Basin shown in Fig. 65).

Age evidence. Stratigraphically equivalent to four dated skeletal limestone units in S.A. part of Murray Basin: Pata Limestone, Morgan Limestone, Mannum Formation, and Gambier Limestone (Lawrence, 1966). On stratigraphic evidence, Duddo Limestone ranges from Late Oligocene to Middle Miocene. In Vic.D.M. Olney No.1, dated Late Oligocene to Early Miocene by Abele (1970) on foraminiferal evidence. In adjacent areas of S.A., Ludbrook (1957, 1961a) identified Pata Limestone as Middle Miocene age – Middle Miocene components appear absent in Vic.D.M. Olney No.1, where Duddo Limestone overlain by Winnambool Formation of partly equivalent age to Pata Limestone (Brown & Stephenson, 1986).

Characteristics. Lithology, stratigraphic position; geographic location and palaeontology also distinctive. Easily distinguished by lithology from calcareous clays of Ettrick and Winnambool Formations, Bookpurnong beds, and Geera Clay. More micritic, and greater proportion of calcareous clay bands (marl), than other time-equivalent limestone units of Tml.

Environment of deposition. Deposited in Oligo-Miocene 'Murravian Gulf', which at that time covered large part of west Murray Basin. Shallow-marine environment, but water depth varied with time and location, but in general decreased with time; although global sea-level changes caused many fluctuations within Murray Basin. Duddo Limestone graded laterally into restricted marine and lagoonal sediments (Winnambool Formation) near margins of 'Gulf' (Lawrence, 1975; Brown, 1985) – as sea retreated from Murray Basin in Middle Miocene, Winnambool Formation partly regressed back over Duddo Limestone in north and east. In centre of basin, open-marine facies persisted until retreat of sea from Murray Basin at about 11 Ma.

Stratigraphic nomenclature and type section. Named by Lawrence (1966) after Parish of Duddo, north of Murrayville in west Victoria. Standard subsurface section selected by Lawrence (1966) in Duddo No.8 (north of Murrayville) between 76.8–185.6 m – greyish-white limestone, varying in texture from fine to medium-grained, with some sand-sized quartz grains; dominant fossils bryozoa and foraminifera (Lawrence, 1966).

Stratigraphic relationships. Conformable over Ettrick Formation. Interfingers with, and partly enveloped by, Winnambool Formation to north and east. Where upper (regressive) phase of Winnambool Formation absent, disconformable under either Bookpurnong beds or Loxton–Parilla Sands. Lawrence & Abele (1976, fig. 8.4, 1988; Fig. 43) show limited interfingering between Duddo Limestone and Geera Clay.

Hydrogeology. Part of Murray Group aquifer system – one of most important aquifers of Murray Basin (see 'Groundwater').

Data sources. Chapman (1916), Ludbrook (1957, 1961a, 1969a, O'Driscoll (1960), Lawrence (1966, 1975), Abele (1970), Lawrence & Abele (1976, 1988), Woolley & Williams (1978), Brown (1983, 1985), and Brown & Stephenson (1985, 1986).

Unit: Geera Clay of the Murray Group
Age: Late Oligocene to Middle Miocene
Map symbol: Tmg
Synonyms: 'Pata Limestone Equivalents'

Lithology. The Geera Clay consists mainly of black, olive grey, dark-grey or dark-green silty mud, silt, clay, and minor dark sand. The silt and clay are predominantly terrigenous in origin but are glauconitic, pyritic, locally calcareous (marly) and locally carbonaceous. In places, they include dolomite, dolomitic siltstone and sandstone interbeds, as well as intercalated calcareous clay (marl) of the Ettrick and Winnambool Formations. X-ray diffraction analyses indicate that, in fact, much of the silty mud consists of silt and clay-size quartz, rather than clay (Radke, 1987; Brown & Radke, 1989). In-situ fossils, in addition to sand-size fragmented skeletal material, are preserved throughout the mud. Towards the north and east, the silty mud is increasingly carbonaceous and includes intercalated peat, humic debris, and carbonaceous sediments of the Olney Formation. Limonitic and glauconitic faecal pellets are common. Angular silt and detrital quartz sand grains and carbonate clasts, in addition to subrounded ferruginous clasts, occur within a clay or humic clay matrix.

The silty mud is poorly consolidated and generally friable to plastic in texture. The main clay minerals have been identified as smectites, kaolin and illite. Other minerals include authigenic pyrite, hematite, siderite, natrojarosite, and dolomite (Lawrence, 1975). The dark colour of the Geera Clay is possibly due to a high humic content and/or the

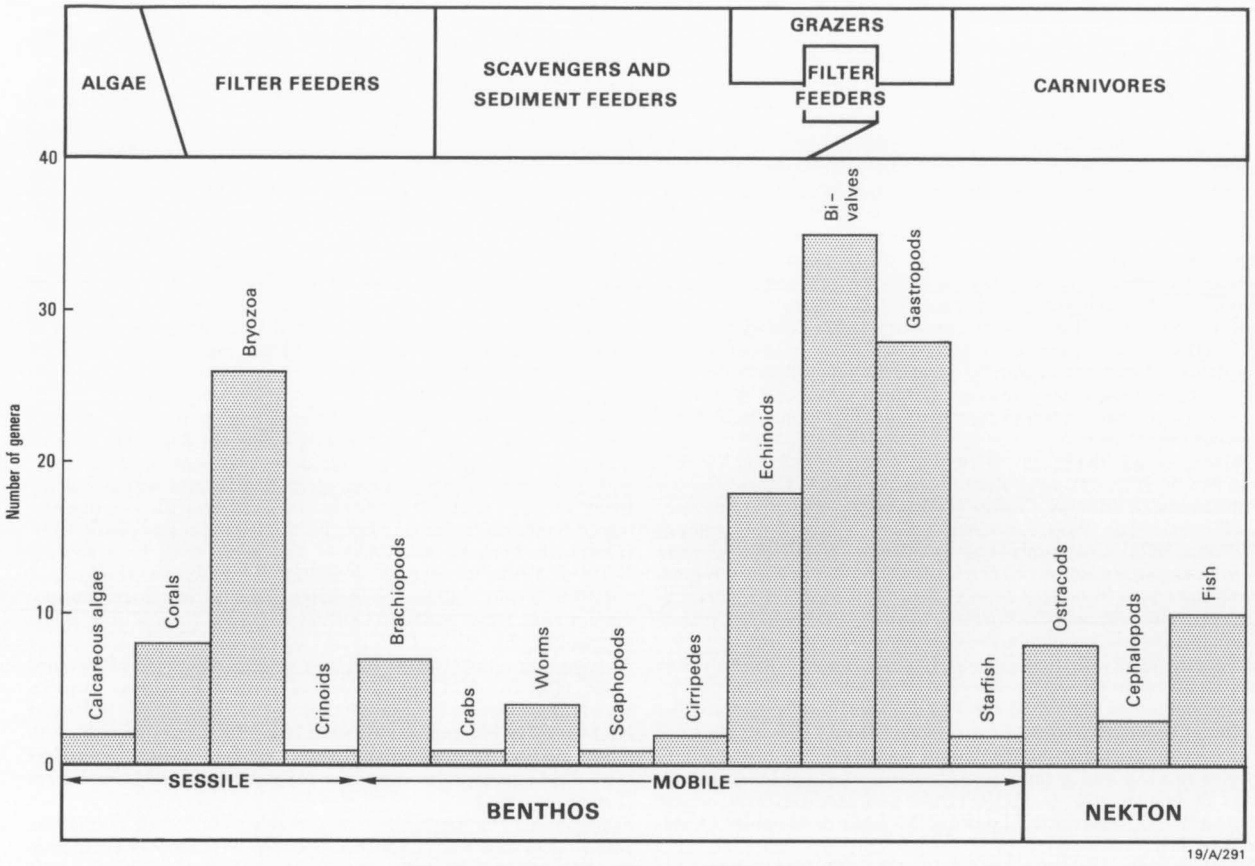


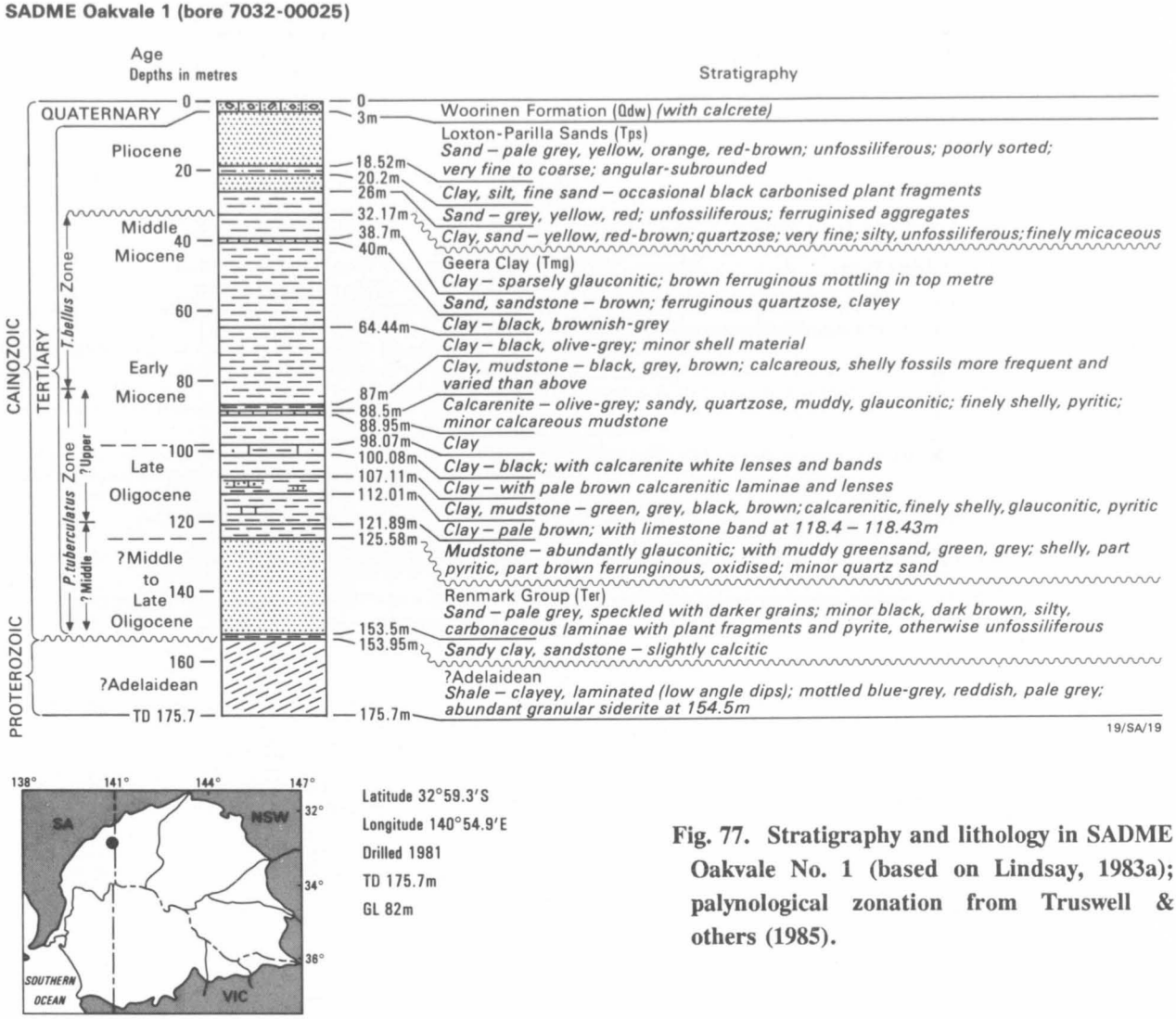
Fig. 76. Macrofauna of Duddo Limestone.

presence of abundant iron minerals, particularly in the form of disseminated iron sulphides (Lawrence, 1966). In bores such as SADME Oakvale No.1 (Fig. 77), in OLARY, where the Geera Clay is disconformably overlain by Pliocene sediments, the top metre of the formation is a surface of erosion or weathering, and is brown in colour with ferruginous mottling. Radke (1987) identified a number of lithofacies assemblages encountered in Piangil West-2 bore (Fig. 78; Table 24). He particularly noted that plastic smectite-rich clay comprises only 6% of the sequence and that most of the fine-grained sediment consists of silt and clay-size quartz.

Distribution and thickness. The Geera Clay has been encountered in boreholes in an arcuate zone beneath the northwestern Victorian, southwestern New South Wales, and northern South Australian sectors of the basin (Fig. 79; Plate 9). Brown & Stephenson (1986) recorded the presence of the unit in 163 boreholes of which 149 penetrated the entire thickness of the formation. The average thickness encountered was 44.6 m, but the thickest sequence yet recorded is 174 m in bore 116-8001 in SWAN HILL. Thicknesses of over 100 m have been encountered in parts of ANABRANCH, BALRANALD, POONCARIE and SWAN HILL. Isopachs of the Geera Clay (Plate 9) indicate that the formation thins towards the north and east, where it interfingers with carbonaceous sand, silt and clay of the Olney Formation. The formation also progressively thins to the south and west, where it is intercalated with, and laterally replaced by, calcareous clay of the Winnambool Formation and limestone of the Murray Group (Figs 45, 79).

Outcrop. The Geera Clay is entirely concealed beneath younger Tertiary sediments and is not exposed at the surface of the basin.

Internal geometry and log characteristics. Isopachs indicate the unit forms an arcuate elongate wedge of sediment (Plate 9). Borelogs show that the formation forms a thick bioturbated unit, with little preservation of distinct bedding, apart from local fine laminations, minor hardgrounds, and cemented siltstone and sandstone interbeds. Few geophysical well logs have been run through the Geera Clay, but the available Gamma and Self Potential Resistivity logs are generally highly serrated. The contact with underlying sands of the Olney Formation is generally abrupt, as is the upper contact where the formation is overlain by the Loxton–Parilla Sands. Elsewhere, the contact with overlying or underlying Winnambool



Latitude 32°59.3'S
Longitude 140°54.9'E
Drilled 1981
TD 175.7m
GL 82m

Fig. 77. Stratigraphy and lithology in SADME Oakvale No. 1 (based on Lindsay, 1983a); palynological zonation from Truswell & others (1985).

Formation or interfingering Olney Formation is gradational. The contact with disconformably overlying but lithologically similar Bookpurnong beds is difficult to identify in many bores.

Palaeontology. In comparison with the limestones of the Murray Group, the Geera Clay has a less-diverse palaeontological fauna, but in terms of fossil abundance it preserves rich assemblages of miliolids, ostracods, foraminifera, and turritellid gastropods. The unit is heavily bioturbated and contains glauconitic faecal pellets and numerous worm tubules, some of which are now pyritised. Lawrence (1975) noted that foraminiferal faunas are poorly developed at the base, but are increasingly diagnostic towards the top of the formation (Lawrence, 1975). In SADME Canopus No.1 (Fig. 80), Ludbrook (1961a) identified thin-shelled foraminifera, minute pelecypods, molluscs, several gastropods and minor quantities of corals, and bryozoa. Foraminiferal assemblages in the Geera Clay in SADME Oakvale No.1 have been described by Lindsay (1983a), and rich, well-preserved palynological assemblages have been described by Truswell & others (1985; Fig. 77), Macphail (1987, 1988a,b), and Macphail & Truswell (1988, 1989).

In Piangil West-2, Radke (1987) reported the following macrofaunal elements, in decreasing abundance: pelecypods, gastropods, echinoids, bryozoa, foraminifera, malacostracans, ostracods, corals, scaphapods, fish teeth, as well as the abundant presence of *Chondrites* and *Ophiomorpha*-like trace fossils. Radke (1987) also noted that the preservation of the calcareous macrofauna is very poor because of partial dissolution of the carbonate. Residual carbonate and mould impressions tend to be friable and powdery, and deteriorate rapidly on exposure to air and drying.

Age evidence. Micropalaeontological age determinations indicate that the Geera Clay ranges in age from Late Oligocene to Middle Miocene (e.g. Ludbrook,

TABLE 24. LITHOLOGY LOG OF GEERA CLAY SECTION, IN VIC.D.M. PIANGIL WEST-2 BOREHOLE

Based on Radke (1987) & Radke (unpublished data, 1988).
Note that in Radke (1987) and Macphail (1988a), Piangil West-2 was inadvertently referred to as Piangil West-1.
Location of borehole shown on accompanying Figure 78.

0 – 9 m Qly

9 – 81.5 m Loxton – Parilla Sands (Tps)

81.5 – ?102 m ?Bookpurnong beds (Tpb)

?102 – 232 m Geera Clay (Tmg)

102 – 106.1 m core loss
106.1 – 109.4 m olive-black clayey silt; burrowed, fossiliferous, pyritic, glauconitic
109.4 – 114.5 m burrow-mottled, light & dark olive-grey, quartzose, glauconitic sand; pyritic; intergradational with burrowed silt & minor gravelly sand; faint relict lamination & ?flasers
114.5 – 119 m core loss
119 – 121 m dark brown to olive-grey burrow-mottled silt, clayey in part, fossiliferous, pyritic
121 – 122 m core loss
122 – 122.9 m ?weathered, crumbly slickensided, olive-black sandy silt
122.9 – 128 m dark olive-grey/black, burrowed silt & sand, grading down to more finely burrowed pyritic silt
128 – 131.4 m brown-black/olive-black clayey silt, mud, silt & minor sand interbanded; burrowed, fossiliferous, pyritic & slickensided; carbonate concretions
131.4 – 134 m interbedded clay predominant; pyritic, cherty dolomitic concretions with fractured & resin coated centres; minor gravelly clay
134 – 134.5 m core loss
134.5 – 140.8 m olive-black/dark olive-grey clayey silt, minor mud & clay; burrows increasingly smaller down sequence, large burrows part occluded by pyrite & resin
140.8 – 143.6 m core loss
143.6 – 146.3 m dark olive-grey burrowed silt – gradational down to burrowed, faintly laminated mud & clayey silt, pyritic, glauconitic
146.3 – 147 m core loss
147 – 155 m dark olive-grey/light-olive grey, burrow-mottled clayey silt & minor mud; fossiliferous, faintly laminated, pyritic
155 – 165.3 m monotonous gradational alternations of dark olive-grey/light olive-grey & olive-grey/yellow-grey, burrow-mottled clayey silt, mud & minor clay; pyritic with goethitic haloes in places
pyritic Ophiomorpha-like burrows increasingly abundant down to underlying sands
165.3 – 170.7 m dark olive-grey/yellow-grey, burrow-mottled, fine, sorted, quartzose sand; glauconitic, shelly, locally indurated & dolomitic; glauconitic & muddy firmgrounds; separate sandy muddy silt & flasered silt, carbonate concretions
170.7 – 174 m dark yellow-brown/light olive-grey, laminated foraminiferal, micaceous silt, clayey to top, sandy to base; abundant graded laminae & flasers
174 – 175.4 m core loss
175.4 – 179 m olive-grey/yellow-grey (laminated) sandy silt, clayey silt; minor micaceous quartzose sand at base, clay at top, flaser structures
179 – 179.6 m core loss
179.6 – 185.8 m dark olive grey/yellow-grey, burrow mottled & laminated clayey silt, minor mud, clay & sandy gravelly clay; fossiliferous, pyritic; oxidized firmgrounds
185.8 – 186 m yellow-orange/yellow-brown, oxidised cobbly gravel
186 – 187.1 m yellow-grey/olive-grey, very fine, quartzose sand, mud fossiliferous, glauconitic, gradational down to olive-grey very fine sand
187.1 – 188 m core loss
188 – 189.8 m light olive-grey, very fine, quartzose sand; tan/dark olive-grey, interlaminated mud; skeletal hash
189.8 – 189.9 m black mud, sand; burrowed
189.9 – 190.8 m core loss
190.8 – 191 m brown/black & light olive-grey, interlaminated mud, sand; burrowed
191.5 – 192.3 m olive-grey very fine quartzose sand; carbonate cement; concretions
192.3 – 192.9 m brown/black pebbly mud, sand; skeletal hash grading down to sand, mud, skeletal; carbonate cement
192.9 – 194.4 m olive-grey, fine, quartzose sand, glauconitic; skeletal hash
194.4 – 195.1 m mottled olive/black mud, pelletal glauconite, sand; grading down to olive grey sand with glauconitic matrix
195.1 – 196 m core loss
196 – 196.2 m olive-black/light olive-green bioturbated mud, interlaminated sand; glauconitic
196.2 – 203.5 m olive-grey, very fine quartzose sand; glauconitic matrix; carbonate cement decreasing towards base; skeletal fragments; some pelletal glauconite; some faint mottling at base
203.5 – 203.6 m olive-black mud, interlaminated sand
203.6 – 206 m core loss
206 – 207.1 m olive-grey mottled, very fine, quartzose sand; pelletal glauconite
207.1 – 207.6 m brown-black mud, interlaminated yellow-grey silt
207.6 – 208.5 m core loss
208.5 – 209 m brown black mud at top; olive-grey sand at base; dolomitic cement
209 – 213.5 m core loss
213.5 – 215.2 m olive-grey very fine sand; pelletal glauconite, micaceous; uniform sand at base
215.2 – 216 m core loss
216 – 216.2 m grey-black mud
216.2 – 216.9 m olive-grey very fine sand; pelletal glauconite
216.9 – 218.3 m sand, interlaminated mud; ocherous cobbly sand at top; pyritic, pelletal
218.9 – 219.5 m core loss
219.5 220.9 m olive-grey very fine quartzose sandstone; pelletal glauconite; carbonate cement
220.9 – 221.1 m grey-black mud
221.1 – 222.2 m olive-black sand
222.2 – 222.6 m brown-black mud, bioturbated; pyritic
222.6 – 222.8 m core loss
222.8 – 226.6 m olive-grey very fine quartzose sand; pelletal glauconite; rare shells; some mica
226.6 – 227 m olive-black mud, sand; bioturbated, skeletal
227 – 228 m olive-grey to olive-black uniform sand; interbedded silt; carbonate cement
228 – 228.4 m core loss
228.4 – 230.2 m olive-grey very fine quartzose sand; pelletal glauconite; muddy at top
230.2 – 231 m olive-black mud; silt; increasing bioturbation to base
231 – 232 m core loss

232 – 380 m Olney Formation (Teo) of Renmark Group (Ter) with possible intercalations of Geera Clay to 256 m

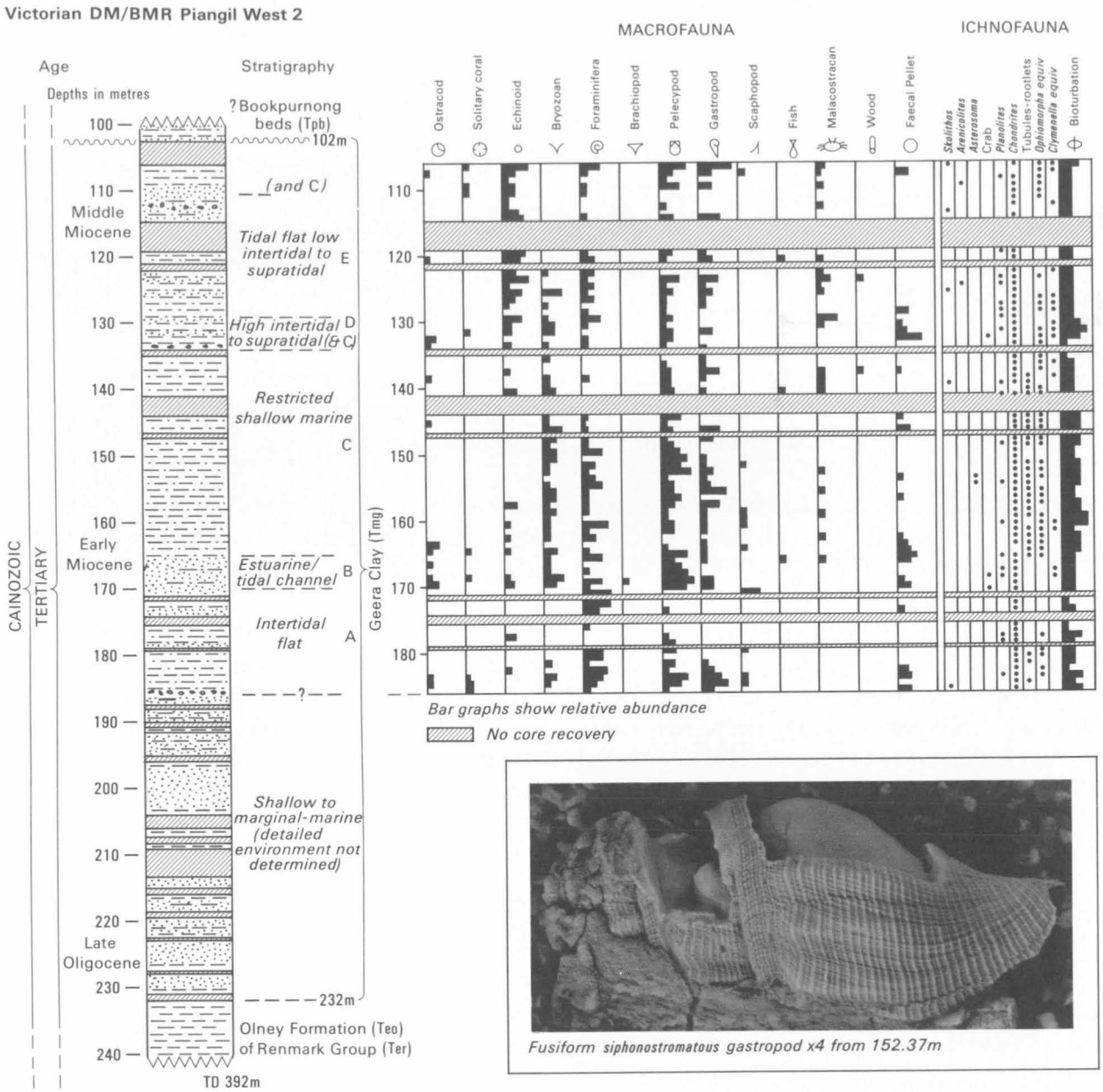


Fig. 78. Lithology log of Geera Clay section encountered in Vic. D.M./BMR Piangil West-2 bore (core stored at BMR core and cutting laboratory). Macrofaunal content, ichnofauna and interpreted environments of deposition of upper 185 m based on Radke (1987); descriptive lithology log shown on accompanying Table. 24.

1961a; Lawrence, 1966, 1975). In terms of local stage names, the foraminiferal assemblages indicate an age range from Janjukian to Bairnsdalian in Victoria (Lawrence & Abele, 1976, 1988). At the base of the Geera Clay in the SADME Oakvale No.1 bore (Fig. 77), Lindsay (1983a) identified foraminifera of the *Guembelitria samwelli* Zone of early Janjukian, Late Oligocene age (equivalent to late Zone P.21). Truswell & others (1985) investigated palynological assemblages in a 93 m thick sequence in the SADME Oakvale No.1 bore and found that deposition commenced in the Late Oligocene and continued into the Middle Miocene. In Vic. D.M. Yellangip No.1 bore (Fig. 82) in HORSHAM, Abele (1970, and in

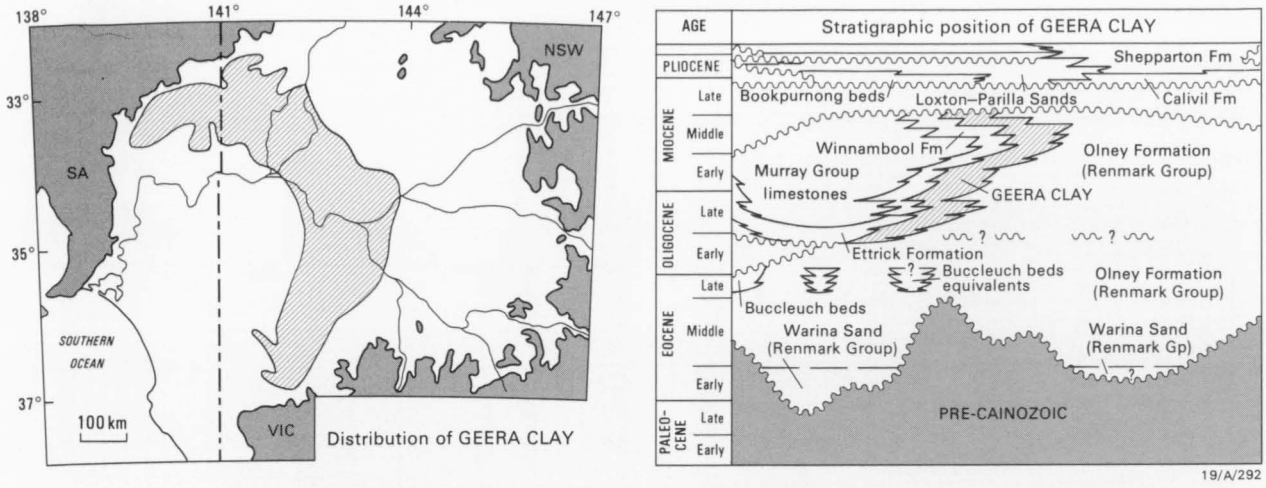


Fig. 79. Distribution and stratigraphic position of Geera Clay.

Lawrence, 1975) identified Zones 5 to 11 (Upper Oligocene to lower Middle Miocene) of Carter (1958a,b) within the Geera Clay. The complete age range is present towards the north and east, but towards the south and west thin sequences of Geera Clay of Late Oligocene age are overlain by transgressive components of the adjacent Oligo-Miocene Winnambool Formation, which are in turn locally overlain by regressive components of Geera Clay of Middle Miocene age (Fig. 79).

Characteristics. The Geera Clay characteristically consists of a dark-grey to black, sticky, silty mud, which preserves an abundant macrofaunal assemblage. However, the abundant bryozoan assemblages – which are typical of the other marine formations of the Murray Group – are greatly impoverished in the Geera Clay. In comparison with sediments of the adjacent Ettrick and Winnambool Formations, the Geera Clay have locally a high carbonaceous content. In some bores, the Geera Clay is difficult to differentiate from interfingering lacustrine clay and peaty sediments of the Olney Formation, which are, however, more carbonaceous and lithologically more variable. In many bores beneath northern and eastern areas, the fine clastics of the Geera Clay are also difficult to differentiate from overlying marine clay of the Upper Miocene–Lower Pliocene Bookpurnong beds. The Bookpurnong beds, however, typically have an abundant, bivalve-rich megafauna and are generally siltier and lighter in colour than the dark muds of the Geera Clay.

Interpretation of environment of deposition. The predominance of shallow-marine faunas, and presence of glauconitic faecal pellets, indicate that the Geera Clay was deposited in mainly shallow to marginal-marine environments. However, the poor representation of bryozoa, and the abundance of miliolids and ostracods, in combination with the relative lack of faunal diversity in comparison with the marine carbonate formations to the south and west, suggest that part of the formation was deposited under ecologically restricted conditions. The presence of pyrite in the black muds, in combination with the pervasive presence of bioturbation, fine laminae (where preserved), and abundant gastropods are consistent with local deposition in restricted shallow-marine or lagoonal settings. In addition, the intercalated dolomite and dolomitic siltstone and sandstone is possibly indicative of inter-tidal/tidal-flat deposition.

The locally carbonaceous interbeds, and intermittent presence of grass and sedge pollen, as well as swamp-related freshwater dinoflagellate and algal assemblages (Truswell & others, 1985), suggests intercalation of, or at least close proximity to, freshwater swamps and fluvio-lacustrine floodplains to the north and east. In addition, the dominance of fine-grained terrigenous clastics, in combination with the general absence of the coarser sediments typical of the Olney Formation or carbonates of the Murray Group calcarenites, suggests that the Geera Clay was deposited partly in extensive shallow to marginal-marine interdistributary bays, proximal to deltaic sources of fine clastics. The local presence of cross-cutting estuarine/deltaic tidal channel sands linking the Olney Formation with the calcarenitic limestone of the Murray Group might be predicted in areas, such as beneath the western extremity of the Riverine Plain, but such sands have only locally been recorded in borehole sections.

SADME Canopus 1

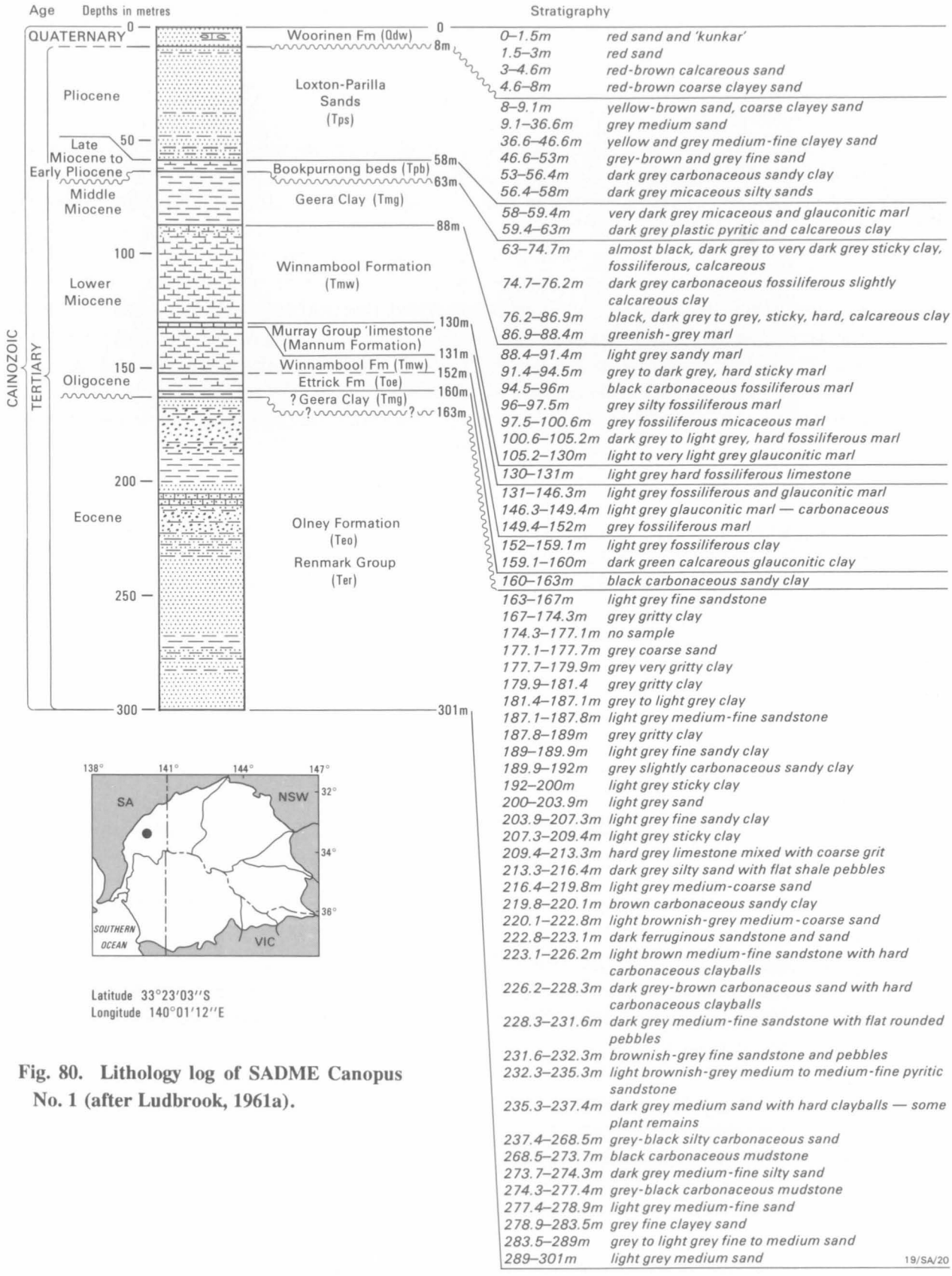


Fig. 80. Lithology log of SADME Canopus No. 1 (after Ludbrook, 1961a).

As discussed by Brown & Radke (1989), the environmental indicators noted above are consistent with deposition of the formation in a range of shallow and marginal-marine, interdistributary bay, lagoonal, tidal-flat, and paralic swamp settings (see 'Cainozoic Sedimentation Patterns').

Stratigraphic nomenclature. The formation was named by Lawrence (1966) after the Parish of Geera, 40 km south of Robinvale in northwest Victoria.

Synonyms. Black, marginal-marine silty mud and clay of Oligocene–Miocene age in RENMARK, CHOWILLA and OLARY in the northwest of the basin (e.g. SADME Canopus No.1, Fig. 80), are of similar age and lithology to the Geera Clay. They were previously described as 'Pata Limestone Equivalents' by Ludbrook (1961a) and Rogers (1978). The uppermost silty clay is certainly time-equivalent to the Middle Miocene Pata Limestone; however, much of this unit is also time-equivalent to the Oligo-Miocene Ettrick Formation, Geera Clay, Winnambool Formation, Mannum Formation, Morgan Limestone and Olney Formation. This silty clay has therefore been correlated with the stratigraphically similar Geera Clay.

Type section. The type section of the Geera Clay is located in a 30.5 m thick interval between 149.3 m and 179.8 m in the Vic. D.M. Geera No.1 bore (634-1) in BALRANALD (Lawrence, 1966, 1975). The unit overlies sand and gravel of the Olney Formation, and in turn is overlain by calcareous clay of the Winnambool Formation. The section consists mainly of light olive to dark-grey fossiliferous and glauconitic clay, but includes thin interbeds of calcareous clay, dolomite, dolomitic siltstone, and dolomitic sand (Lawrence, 1966, 1975). No detailed description of the type section has been published, but material from the section is held at the core and cuttings store of the Victorian Department of Industry, Technology and Resources, Melbourne.

Stratigraphic relationships. In the east and north, the Geera Clay conformably overlies and is laterally intercalated with Late Oligocene to Middle Miocene fluvio-lacustrine sediments of the Olney Formation. Locally, in the north and east a thin truncated layer of sandy marine sediment of the predominantly non-marine Olney Formation conformably overlies Middle Miocene components of the Geera Clay. In the west and south, the base of the Geera Clay interfingers with calcareous clay of the Oligocene Ettrick Formation, and higher sequences are intercalated with, and are locally overlain by transgressive calcareous clay of the Oligo-Miocene Winnambool Formation (Figs 45, 79). Locally, regressive Middle Miocene components towards the top of the Geera Clay conformably overlie the Winnambool Formation. The Geera Clay thus partly envelops the Winnambool Formation, and is in turn partly enveloped by the Olney Formation. Less commonly, in some bores the unit is intercalated with limestone formations of the Murray Group.

Aquifer characteristics. The Geera Clay forms an important component of the Mid-Tertiary low permeability barrier which separates aquifers of the Renmark Group from those of the Murray Group (see Fig. 172). The presence of this permeability barrier is thought to result in the diversion of groundwater flow into overlying aquifers and locally to the surface. Visual estimations by Radke (1987) indicated that initial bioturbation-enhanced microscopic and macroscopic porosities ranged from 0–30%, but were drastically reduced to the present-day range of 0–7% by early diagenetic cementation by clays, carbonates, and pyrite, as well as by compaction.

Data sources. Descriptions of the Geera Clay are given in Lawrence (1966, 1975), Lawrence & Abele (1976, 1988), and in a number of petroleum well completion reports and water bore logs. The hydrogeological significance of the formation is described by Brown (1989) and Brown & Radke (1989). A description 'Pata Limestone Equivalents' (Geera Clay) is given in Ludbrook (1961a). Foraminiferal assemblages are documented in Lindsay (1983a), and detailed and systematic descriptions of the palynological content of the formation are recorded in Truswell & others (1985), Macphail (1987, 1988a,b), and Macphail & Truswell (1989). A detailed and comprehensive description of the sedimentology and diagenesis of the Geera Clay section encountered by Piangil West-2 borehole is contained in Radke (1987) and Brown & Radke (1989).

Unit: Winnambool Formation of the Murray Group
Age: Late Oligocene to Middle Miocene – mainly Early Miocene
Map symbol: Tmw
Synonyms and equivalents: 'Morgan–Mannum Equivalents', 'Middle Marly Unit' of Morgan Limestone

Lithology. The Winnambool Formation consists mainly of poorly consolidated, richly fossiliferous, grey, blue-grey and pale-green calcareous clay (marl), and silty clay. The formation also includes marly limestone, and thin interbeds of grey skeletal

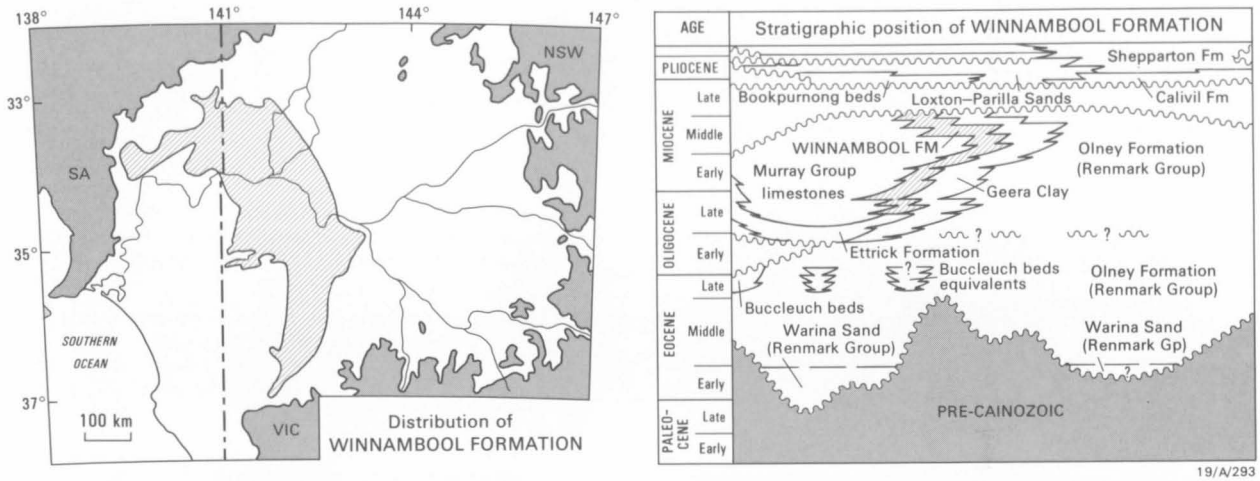


Fig. 81. Distribution and stratigraphic position of Winnambool Formation.

calcisiltite and calcarenite, as well as thin bands of micritic limestone. The sediment is generally soft, and plastic to friable in texture, although the micritic layers are well-cemented and hard. In many bores the calcareous clay is highly glauconitic and olive-grey in colour. The carbonate fraction within the calcareous clay, consists partly of fine calcarenitic skeletal debris, partly of fine-grained detrital intraclasts of micrite, and partly of micritic cement.

Distribution and thickness. The Winnambool Formation is entirely concealed, but has been encountered by bores drilled into an arcuate zone within west-central parts of the basin, beneath northwestern Victoria, extending through southwestern areas of New South Wales, into north-central areas in South Australia (Fig. 81). The unit is thickest in the central-west of the basin, and thins abruptly to the north and east, and progressively to the south and west (Plate 7). Brown & Stephenson (1986) recorded 60 bores which have penetrated the entire formation. The average thickness encountered was 37 m. In detail, however, thicknesses are highly variable, reflecting the complex facies relationships between the intercalated units of the Murray Group. The formation is thickest in those bores where the adjacent limestone of the Murray Group and black fine clastics of the Geera Clay are absent. The thickest recorded sequence encountered to date is 113 m in W.R.C. bore 36464 in MILDURA. Other bores which have encountered considerable thicknesses are bore 6830-0286 (105 m) in CHOWILLA, bore 6829-0802 (105 m) in RENMARK, and bore 4769 (103 m) in ANABRANCH (Brown & Stephenson, 1986).

Outcrop. The formation is entirely concealed.

Internal geometry and log characteristics. Borehole sections are thick and indistinctly stratified, with the exception of interbeds of micritic limestone and skeletal calcarenite. These are generally only a few centimetres thick and are described as 'hard bands' on drillers logs. Few geophysical logs have been run in the Winnambool Formation, but the available Gamma and Self Potential logs are slightly serrated and bell-shaped. A relatively high Gamma response reflects the high glauconite content of the formation. The upper contact of the unit is sharp, where it is overlain by sand of the undifferentiated Loxton–Parilla Sands. In contrast, the contact with underlying, interfingering or overlying Geera Clay is gradational. The contact with underlying or intercalated limestone units is also gradational.

Palaeontology. The Winnambool Formation is a highly calcareous unit, which preserves abundant and diverse microfaunal and macrofaunal assemblages. It has numerous pelecypods, bryozoa, echinoids, gastropods and foraminifera, including common to abundant miliolids and ostracods. In comparison with the limestone of the Murray Group, the formation contains slightly less echinoid and bryozoan skeletal debris, but in comparison with the Geera Clay it has a more diverse macrofaunal assemblage. Much of the fine carbonate fraction of the formation includes comminuted silt-sized skeletal debris. Many of the macrofossils and in particular the gastropods are well preserved and intact.

Age evidence. Micropalaeontological assemblages have been variously dated from Late Oligocene to Middle Miocene in age (Longfordian to Bairnsdalian Stages), but the formation appears to be predominantly of Early Miocene age. The *Orbulina universa* Zone 11 of Carter (1958a,b), equivalent to

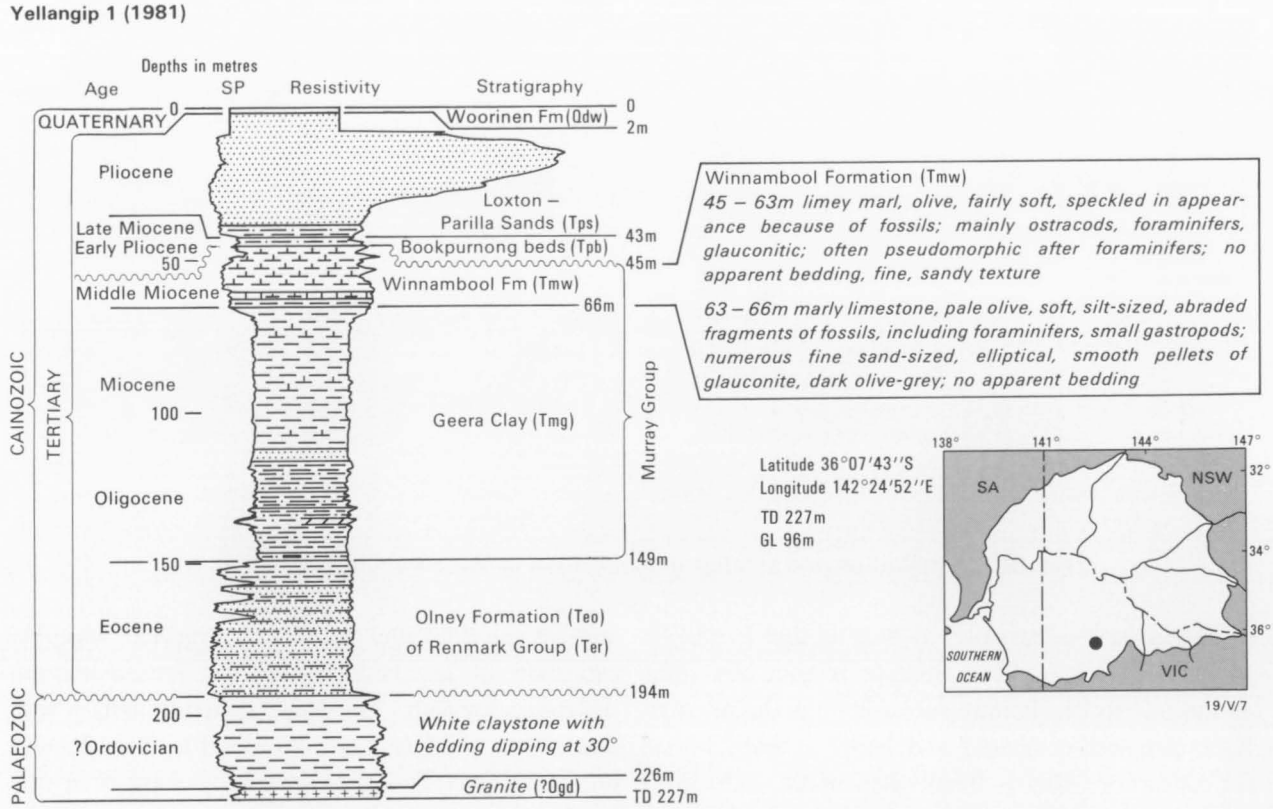


Fig. 82. Lithology log Vic. D.M. Yellangip No. 1 (after Lawrence, 1975).

the local Bairnsdalian Stage of Middle Miocene age, has been identified in the Vic. D.M. Yellangip No.1 bore (Fig. 82; Abele, 1970; Lawrence, 1975). Stratigraphically equivalent sediments intercalated within the limestone units of the Murray Group to the south and west are mainly Early Miocene in age (see 'Cadell Marl' Table 20).

Characteristics. The boundary between the Winnambool Formation and underlying or overlying Geera Clay is placed at the level at which fossiliferous blue-grey clay is replaced by less fossiliferous non-calcareous dark silty mud and clay. In some bores, in the absence of palaeontological control, the calcareous clay of the Winnambool Formation can be confused with the older lithologically similar sediment of the Ettrick Formation. In most areas, however, the two formations can be separated on distribution and age control (see 'Remarks').

In places, the Winnambool Formation can also be difficult to differentiate from overlying similar calcareous clay of the Bookpurnong beds. The Bookpurnong beds are generally darker, are lithologically more variable than the Winnambool Formation, and extend farther to the southwest (see Fig. 84). In addition, the Bookpurnong beds are characterised by the presence of a distinctive bivalve-rich macrofauna.

Interpretation of environment of deposition. The fossil content of the formation, in combination with the presence of glauconite, indicates deposition in shallow-marine, inner-shelf neritic environments. The high proportion of calcareous clay suggests low-energy protected settings, in contrast to those of the shoal calcarenites of the Murray Group. This is supported by the presence of well-preserved and intact macrofossils, particularly gastropods. On the other hand, the abundant presence of comminuted skeletal debris indicates a regular influx of material winnowed from higher-energy sources. In comparison with the limestone of the Murray Group, the formation has a lower proportion of coarse echinoid and bryozoan skeletal debris, and a greater terrigenous content. In comparison with the Geera Clay, however, the Winnambool Formation preserves a more diverse marine macrofaunal assemblage, a higher calcareous content, lower terrigenous content, and less carbonaceous detritus. The Winnambool Formation was deposited seaward of the Geera Clay, but landward of the limestone of the Murray Group. The formation is therefore thought to have been deposited on restricted-circulation platform environments, ranging from shallow-marine to lagoonal.

Stratigraphic nomenclature. The formation was named by Lawrence (1966) after the Parish of Winnambool, 50 km south of Robinvale in northwest Victoria.

Synonyms and correlative units. The Winnambool Formation grades laterally into Miocene limestone of the Murray Group, to the south and west. Some bores have encountered transitional marly limestone, which in CHOWILLA for example was described by Ludbrook (1961a) as 'Morgan–Mannum Equivalents'. In several petroleum exploration wells, such as A.O.C. North Renmark No.1 (Grasso, 1963) and Beach Berri North No.1 (Laws & Heisler, 1967), calcareous clay overlying calcarenite of the Murray Group was stratigraphically placed in Pata Limestone. Brown & Stephenson (1986) placed most such 'marly' sediments of Late Oligocene–Miocene age in the Winnambool Formation (see 'Remarks').

Towards the western margin of the basin, the Cadell Marl Lens of the Morgan Limestone , the synonymous 'Gastropod Bed' of the 'Middle Murravian Series' of Tate (1885), and other calcareous clays such as the 'Middle Marly Unit' of the Morgan Limestone (Lindsay & Bonnett, 1973), are lateral equivalents of the Winnambool Formation, and could be considered to be component parts of a single lithostratigraphic unit. They differ, however, in macrofaunal content (see Tables 20, 21).

Type section. The nominated type section of the Winnambool Formation is the interval between 104 m and 149 m in the Vic.D.M. Geera No.1 bore (bore 634-1), located in BALRANALD (Lawrence, 1966). It consists of 45 m of medium to light-grey glauconitic marly limestone and marly clay, and has common gastropods, pelecypods and minor bryozoal skeletal debris. Lawrence (1966) noted that the type section is lithologically more uniform than that encountered in many other bores.

Stratigraphic relationships. The Winnambool Formation conformably overlies, and is normally indistinguishable from, the lithologically similar Ettrick Formation. To the south and west, the formation is extensively intercalated with, and conformably overlies, limestone units of the Murray Group. To the north and east, the formation conformably overlies and partly interfingers with black silty mud of the Geera Clay. In several bores, especially on ANABRANCH, regressive components of the Geera Clay also partly overlie the Winnambool Formation, so that Geera Clay forms an envelope around the northern margin of the Winnambool Formation (Figs 45, 81). In a few bores, the Winnambool Formation directly overlies sand and carbonaceous clay of the Olney Formation. The formation is mainly disconformably overlain by lithologically similar calcareous clay and silt of the Bookpurnong beds, but locally is also disconformably overlain by the Loxton–Parilla Sands (Loxton Sands in S.A. and Parilla Sand in Victorian nomenclature).

Aquifer characteristics. The unit forms part of the Mid-Tertiary low permeability barrier separating aquifers of the Renmark Group from those of the Murray Group (see Fig. 172). The clay (marl) is generally of low porosity and low permeability, and limestone interbeds hold highly saline groundwater. The unit has therefore not been extensively drilled.

Remarks. The Winnambool Formation is predominantly of Late Oligocene to Mid-Miocene age, whereas the lithologically similar Ettrick Formation is predominantly Oligocene in age (see 'Ettrick Formation'). The two formations are probably component parts of a single time-transgressive unit, but the Ettrick Formation underlies almost the entire southwest of the basin (Fig. 58), whereas the Winnambool Formation is confined in distribution to an arcuate zone underlying west-central areas (Fig. 81). Where practicable, Brown & Stephenson (1986) assigned Oligocene calcareous clay (marl) to the Ettrick Formation, and Oligo-Miocene equivalents to the Winnambool Formation. The combined distribution and thickness of these two units are shown on Plate 7.

In some bores in northern South Australia and southwest Victoria, Miocene calcareous clay, which is now thought to be part of the Winnambool Formation was previously placed in the Ettrick Formation. In northwestern Victoria, calcareous clay (marl), previously logged as Upper Miocene–Pliocene Bookpurnong beds in some bores (e.g. Vic.D.M. Olney No.1, Fig. 50; Lawrence, 1975; Lawrence & Abele, 1976, 1988), are now thought to be a composite of Miocene Winnambool Formation and disconformably overlying Upper Miocene–Pliocene Bookpurnong beds.

Data sources. Descriptions of the Winnambool Formation are given in Lawrence (1966, 1975), Lawrence & Abele (1976, 1988) and Brown & Radke (1989). Similar sediments, previously named 'Morgan–Mannum Equivalents' or 'Pata Limestone Equivalents' have been described from the SADME Canopus No.1 bore (Fig. 80; Ludbrook, 1961a) and in a number of petroleum exploration wells such as A.O.G Wentworth No.1 (188–207 m, Fig. 39; Rose, 1962a), A.O.G. Lake Victoria No.1 (113–137 m, Fig. 39), A.A.O. Morkalla No.1 (110–131 m, Fig. 39), and Sunset No.1 (134–159 m, Fig. 36; Der-

rington & Anderson, 1970).

Unit: Olney Formation of the Renmark Group (see Chapter 7)
Age: Eocene to Middle Miocene
Map symbol: Teo

Several stratal breaks occur within the Olney Formation of the Renmark Group, and as discussed previously, the Oligocene–Middle Miocene components of the formation (which are age-equivalent to the Murray Group) are generally difficult to distinguish on lithology from older Eocene–Lower Oligocene components (see 'Renmark Group' and 'Olney Formation'). In this Bulletin, the variously dated components are therefore regarded as parts of a single lithologic unit, and descriptions of the Oligo-Miocene components have been included in the previous chapter – 'Cainozoic stratigraphy – Lower to Mid-Tertiary sequence'.

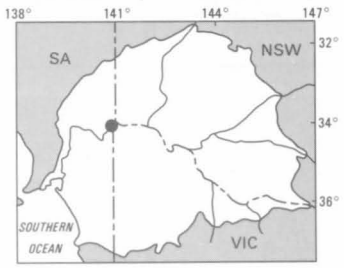


Fig. 83. Cliffs of eroded Loxton–Parilla Sands under ferruginised Karoonda Surface, adjacent to Murray River at proposed Chowilla damsite (southeastern CHOWILLA).

CAINOZOIC STRATIGRAPHY – UPPER TERTIARY SEQUENCE

Upper Tertiary marine and marginal-marine sediments underlie much of the Mallee region of the western Murray Basin, whereas Upper Cainozoic fluvio-lacustrine sediments of the Wunghnu Group underlie the southern and northern margins of the basin, as well as most of the Riverine Plain and adjacent highland valleys in the east. In the west, shallow-marine, Upper Miocene to Lower Pliocene fine clastics of the Bookpurnong beds form the base of the sequence, and are overlain by Upper Miocene to Pliocene shallow-marine, marginal-marine, estuarine, and fluvial quartz sands of the Loxton–Parilla

Sands. In South Australia, these have been differentiated into the marginal-marine, estuarine to fluvial Lower Pliocene Loxton Sands (Table 25), and younger fluvial Upper Pliocene Parilla Sand (Table 26). At the western margin of the basin, the later unit is associated with Upper Pliocene estuarine oyster beds of the Norwest Bend Formation. In the east, the non-marine Wunghnu Group consists of basal, relatively thin, Upper Miocene–Lower Pliocene coarse quartz sands and gravels of the Calivil Formation, with intercalated kaolinitic clays constituting the Torrumbarry Clay (see Table 29). These are overlain by thicker Pliocene to Quaternary silt, clay and sand of the Shepparton Formation. Similar, fine-grained Upper Pleistocene to Holocene fluvio-lacustrine sediments of the Coonambidgal Formation (see Chapter 10) are entrenched within the upper surface of the Shepparton Formation. Equivalents of both formations extend into the Mallee region to the west, particularly within the confined valleys of the modern rivers.

Unit: Bookpurnong beds
Age: Late Miocene to Early Pliocene
Map symbol: Tpb
Synonyms: Bookpurnong Beds, Bookpurnong Formation, 'Kalimnan Series'

Lithology. The Bookpurnong beds consist mainly of poorly consolidated to plastic, brown or greenish-grey calcareous clay (marl), silt and minor sand. The carbonate content is high, with lesser amounts of glauconite and mica. Although clay is dominant, quartz sand and silty facies are locally important. The formation is also carbonaceous in places. Shells and other fossil debris form a significant minor component of the Bookpurnong beds.

Distribution, thickness, and geometry. The Bookpurnong beds are widely distributed throughout the western Murray Basin (Fig. 84; Plate 14). They cover a more restricted area than do the underlying marine sediments of Late Oligocene to Middle Miocene age, and were deposited mainly in the depocentre of the central-western Murray Basin. To the southwest, the Bookpurnong beds onlap eroded limestones of the Pinnaroo Block, over which they are mainly absent – possibly because of erosion, but probably because the Block formed a topographic high at the time of deposition of the Bookpurnong beds. To the north, Bookpurnong beds also extend across those areas of western New South Wales which overlie pre-Cainozoic infrabasins: this is thought to be a result of differential subsidence.

The Bookpurnong beds are roughly lenticular in cross-section and have a plate-like geometry, with maximum thickness in the central-west of the basin. Thickness ranges from a few metres near the margins of its distribution (Fig. 84; Plate 14) up to 50 m near the tri-state border (Brown & Stephenson, 1986); the type section is 15 m thick (Fig. 85). The unit is almost entirely confined to the subsurface, cropping out only on the south bank of the Murray River near the town of Loxton (although this cliff section is visible only at times of low water level, such as during droughts).

Palaeontology. The Bookpurnong beds have a rich macrofauna dominated by bivalves (Fig. 86): representatives of the genera *Nucula, Nuculana*, *Leiopyrga*, *Seripecten*, *Limopsis*, and *Ledella* are particularly common. Other common shells include the

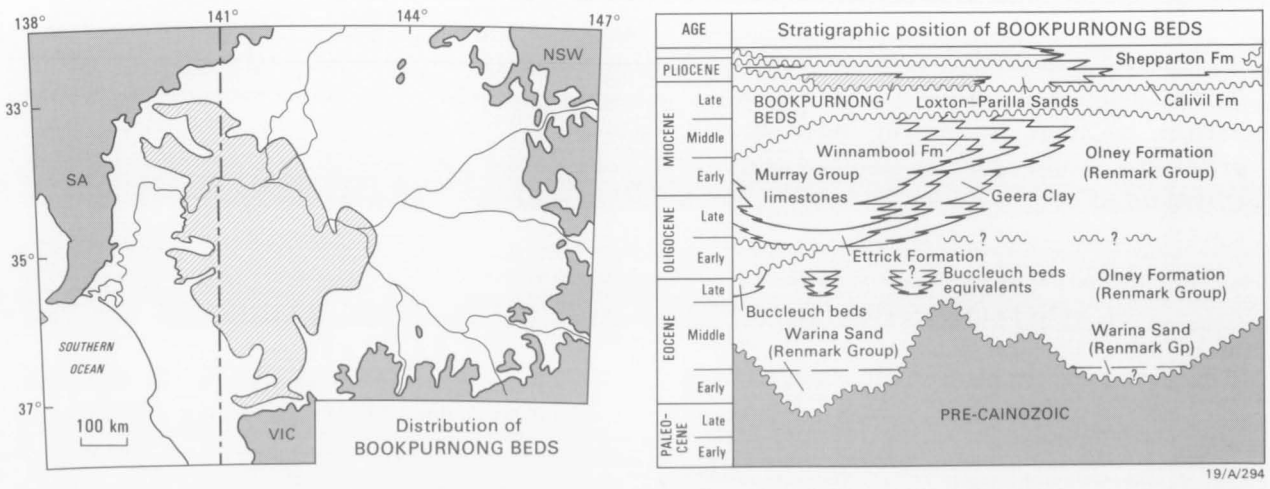


Fig. 84. Distribution and stratigraphic position of Bookpurnong beds.

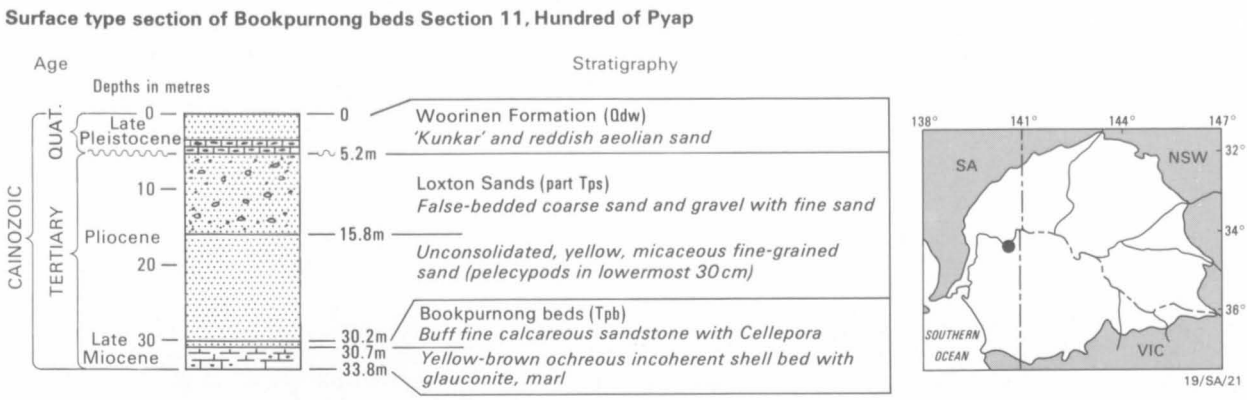


Fig. 85. Surface type section of Bookpurnong beds, exposed by Murray River on Section 11, Hundred of Pyap, 4 km downstream from Loxton (RENMARK); first examined by Howchin (1929), measured and sampled by Spence (1958), and published in Ludbrook (1961a); section continues below water line and degree of exposure is dependent on river level.

gastropod *Turritella* and the scaphopod *Dentalium*; details of recorded genera are given in Appendix 6. The unit also preserves a rich microfauna (Ludbrook, 1957, 1961a); miliolid foraminifera are particularly common.

Ecologically, the fauna of the Bookpurnong beds belongs to the vital-pantostrate biofacies of Schafer (1962). This biofacies is characterised by permanent benthonic biocoenoses (life assemblages), and taphrocoenoses (death assemblages) of nektonic and planktonic animals; bedding in this case has been largely obliterated by benthos activity. This biofacies is characteristic of areas with little water agitation, with sedimentation light and of small grain size (Schafer, 1962). The fauna of the Bookpurnong beds (Fig. 86) contrasts with that of the Loxton Sands (see Fig. 95 and Table 25). The Loxton Sands were deposited in far more energetic environments, and the fauna of that unit consists almost entirely of taphrocoenoses.

Age evidence. Ludbrook (1957, 1961a) assigned a Late Miocene age to the Bookpurnong beds, on stratigraphic and limited foraminiferal evidence; however, she later (Ludbrook, 1969a) changed this interpretation to Early Pliocene. Lawrence (1966) thought the Bookpurnong beds ranged from Late Miocene to Early Pliocene, an opinion shared by Brown (1983), who related the deposition of the Bookpurnong beds and the Pliocene Sands to a major transgressive–regressive cycle between 6.6 Ma and 2.8 Ma ago, with the deposition of the Bookpurnong beds commencing in the Late Miocene (Brown, 1985). Unpublished well completion reports by petroleum exploration companies record foraminiferal evidence supporting a Late Miocene to earliest Pliocene age for the Bookpurnong beds.

Characteristics. The Bookpurnong beds are characterised by lithology, stratigraphic position, and by the presence of a distinctive shelly macrofauna. They are distinguished from the underlying Murray Group limestones and the overlying Pliocene sands by lithology. In places, the Bookpurnong beds show some lithological similarities to both the Winnambool Formation and the Geera Clay, so that confusion can arise in identifying the boundaries of the formations. The Bookpurnong beds are, however, distinguished from the other two units by palaeontology, and in particular by the presence of a distinctive bivalve assemblage of *Pecten*.

Environment of deposition. The Bookpurnong beds were deposited during a Late Miocene to Early Pliocene marine transgression into the western Murray Basin. The fauna of the beds is typical of low-energy marine shelf conditions, with little water agitation and low sedimentation rates. We regard the Bookpurnong beds as representing a shallow-marine to lower shore-face facies equivalent of shallow-marine to upper shore-face and littoral sediments of the basal Loxton–Parilla Sands, deposited to the east and north during the transgression. The transgression occurred rapidly, and was followed by a gradual regression of the Pliocene sands (Loxton–Parilla Sands) back over the top of the Bookpurnong beds. In some areas, borehole data show erosional channels in the beds, which appear to have been infilled by Loxton Sands as the regression proceeded. During the Early Pliocene, the muddy, quieter-water sediments of the Bookpurnong beds were completely overlain by the retreating shallow-marine, littoral and

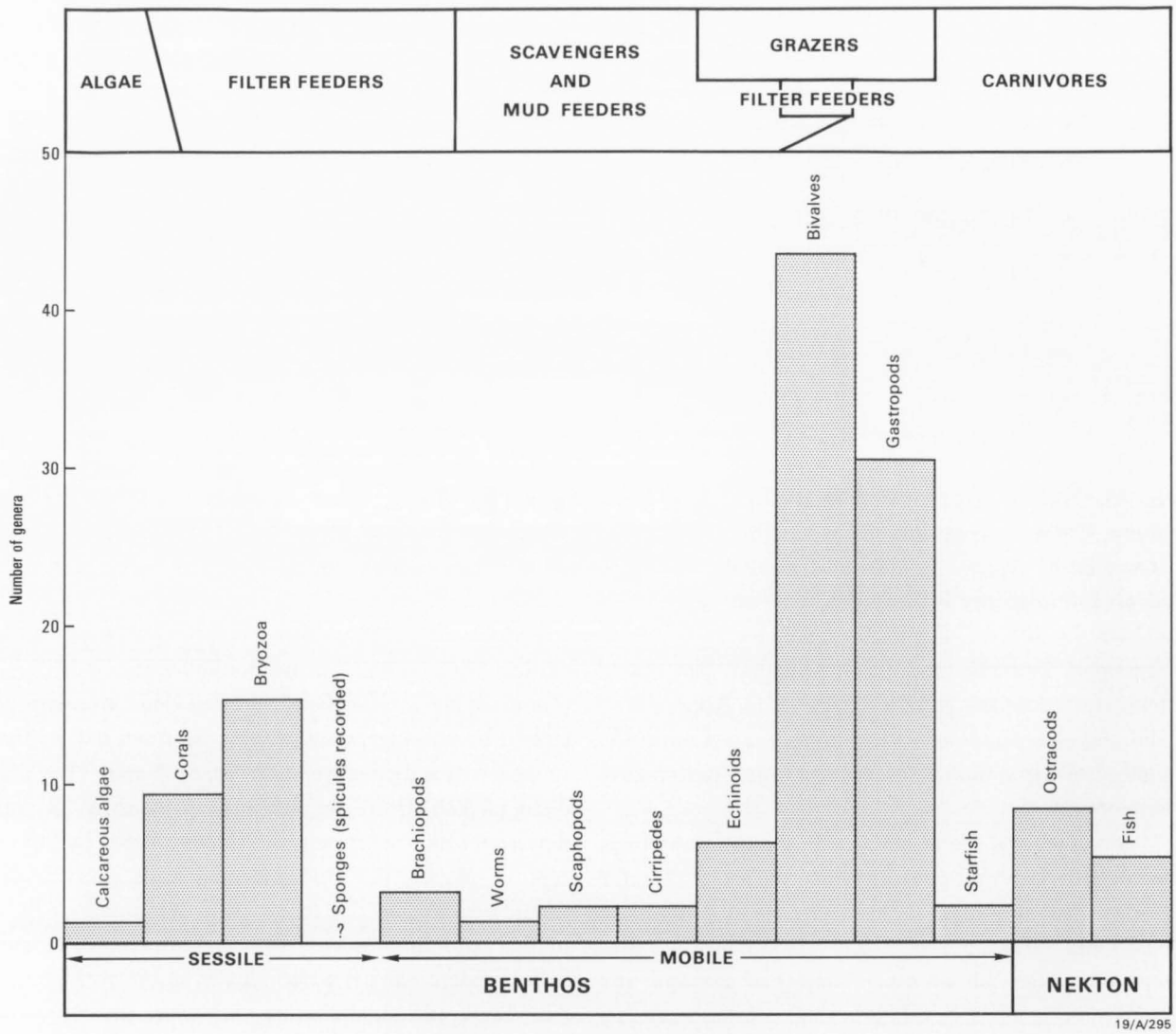


Fig. 86. Known macrofauna of Bookpurnong beds.

strandplain sands of the undifferentiated Loxton–Parilla Sands.

Stratigraphic nomenclature and type section. The 'Bookpurnong Beds' were named by Ludbrook (1957) after the Hundred of Bookpurnong, County Alfred, South Australia; she later (Ludbrook, 1961a) established a type section on Section 11, Hundred of Pyap, on the south bank of the Murray River some 4 km downstream from Loxton. This exposure was described first by Howchin (1929), and subsequently by Spence in 1958 (in Ludbrook, 1961a; Fig. 85). Ludbrook (1961a, p.64–65) gave a detailed description of the fauna present at that location, and also designated a standard subsurface section for the Bookpurnong beds, in Drainage Shaft No.18, Loxton; this bore is located in Section 377, Hundred of Gordon, County Alfred, with the relevant interval being between 23.8 and 38.4 m down the shaft (Fig. 75).

Carter (1985) proposed that the unit be referred to as the 'Bookpurnong Formation', but did not formally define it. The Bookpurnong beds are lithologically variable and the relationships between the various lithofacies are not yet fully understood. In SADME Canopus No.1, for example, the unit consists of black clay and overlies similar black clay of the Geera Clay (Fig. 80). In Vic. D.M. Olney No.1, it consists of marl which is lithologically similar to the underlying Winnambool Formation (Fig. 50; Lawrence, 1975; Lawrence & Abele, 1976, 1988). At this stage, we therefore hesitate to upgrade the status of the unit to that of formation.

Stratigraphic relationships. The Bookpurnong beds disconformably to unconformably overlie the sediments of the Murray Group. These include limestones (Pata Limestone, Morgan Limestone, and Duddo Limestone), calcareous clays (Winnambool Formation), and black silty muds (Geera Clay). In places, these underlying Early to Middle Miocene

units developed an erosional surface prior to deposition of the Bookpurnong beds in the late Miocene; this surface is evident over parts of the Pinnaroo Block, and is equivalent to the Mologa Surface of Macumber (1978a) in the southeast of the Murray Basin.

The Bookpurnong beds underlie, and partly interfinger to the east and north with, the Pliocene Loxton–Parilla Sands: the Loxton Sand in South Australia, and the lower parts of the 'Parilla Sand' in Victoria and New South Wales (the Parilla Sand *sensu stricto*, as originally defined in South Australia does not directly overlie the Bookpurnong beds – see 'Loxton–Parilla Sands'). Woolley (1978) showed the Bookpurnong beds in contact with both the Olney Formation and the Calivil Sand, although Brown (1983) noted that the Bookpurnong beds are mainly laterally separated from the Calivil Formation by basal Loxton–Parilla Sands.

Hydrogeology and economic geology. The Bookpurnong beds form an important aquitard (Upper confining layer) at the base of the Pliocene Sands aquifer system (see Fig. 172). It also caps the Oligo-Miocene Murray Group aquifer system over a large area. O'Driscoll (1960) thought there was some leakage upwards from the Murray Group aquifer system into the Pliocene Sands aquifer system, and recent hydrologic work seems to bear this out (S.R.Barnett, pers. comm., 1982). The permeability of the Bookpurnong beds is limited in most places, but where a sandy facies is present they locally contain saline groundwater (O'Driscoll, 1960). In northern and eastern areas, the Bookpurnong beds locally combine with the Geera Clay, Winnambool and Ettrick Formations to form one contiguous low-permeability barrier separating the Murray Group aquifer system below from the Renmark Group aquifer system to the north and east, and the Pliocene Sands aquifer system above (see Fig. 172). In some western areas, south of the Murray River, marly facies of the Pata Limestone and/or Winnambool Formation combine with the Bookpurnong beds in a similar manner.

Remarks. Lawrence (1966, p.534) suggested that the Bookpurnong beds "are offlap deposits from the upper neritic to littoral zones of the slowly retreating seas of the Murravian Gulf." We believe this to be partly true, but regard the Bookpurnong beds as also including onlap deposits related to the Late Miocene Murravian transgression, and as being deposited in shallow-marine to lower shore-face environments; the Bookpurnong beds are thus a facies equivalent to the lowermost, marine component of the Loxton–Parilla Sands to the east and north. Brown (1983) suggested that deposition of this Upper Miocene to Early Pliocene transgressive–regressive sediment package may have occurred between 6.6 and 2.8 Ma ago. However, work on the Plio-Pleistocene Lake Bungunnia by Stephenson (1986) suggests that the sea may have retreated from the Murray Basin proper as much as 3.5 Ma ago.

Data sources. Publications with information on the Bookpurnong beds include: Chapman (1916), Howchin (1929), Ludbrook (1957, 1961a, 1969a), Spence (1958), O'Driscoll (1960), Lawrence (1966), Firman (1972), Lawrence & Goldberry (1973), Macumber (1978a), Rogers (1978, 1980a), Woolley (1978), Woolley & Williams (1978), Brown (1983, 1985), Brown & Stephenson (1986), and Stephenson (1986).

Unit: Undifferentiated Loxton–Parilla Sands
Age: Late Miocene to Pliocene (mainly Pliocene)
Map symbol: Tps
Component units: Loxton Sands in South Australia (including Upper and Lower Loxton Sands – Table 25); Parilla Sand in South Australia (Table 26); Parilla Sand in Victoria and New South Wales (including Kerang Sand Member, Tragowel Member, and Wandella Sandstone Member – Table 27)
Synonyms: Diapur Sandstone, Werrikooian Series
Contiguous unit: Dorodong Sandstone (Otway Basin)
Associated unit: Moorna Formation (Table 28)

Remarks. In South Australia, Firman (1965b 1966c, 1972, 1973) subdivided the relatively well-exposed Lower Pliocene Loxton Sands seen in river cliffs of the Murray River, into the marginal-marine and estuarine Lower Loxton Sands and the fluvial Upper Loxton Sands (Table 25). He also differentiated the overlying Upper Pliocene Parilla Sand (Table 26), which he interpreted to be entirely fluvial in origin and to represent only the youngest of several Pliocene sand units. In northwestern Victoria, Lawrence (1966) initially named the Pliocene sands 'Diapur Sandstone' after the township of Diapur in HORSHAM. He noted that the Diapur Sandstone can be correlated with the Loxton Sands of Ludbrook (1957) in adjacent areas of South Australia, but decided that lithologies and fossil content were sufficiently different to warrant definition as a separate unit. In the type area, 4 km west of Diapur, the Diapur Sandstone consists almost entirely of slightly micaceous, non-fossiliferous, fine to medium-grained sand, whereas in the type area of

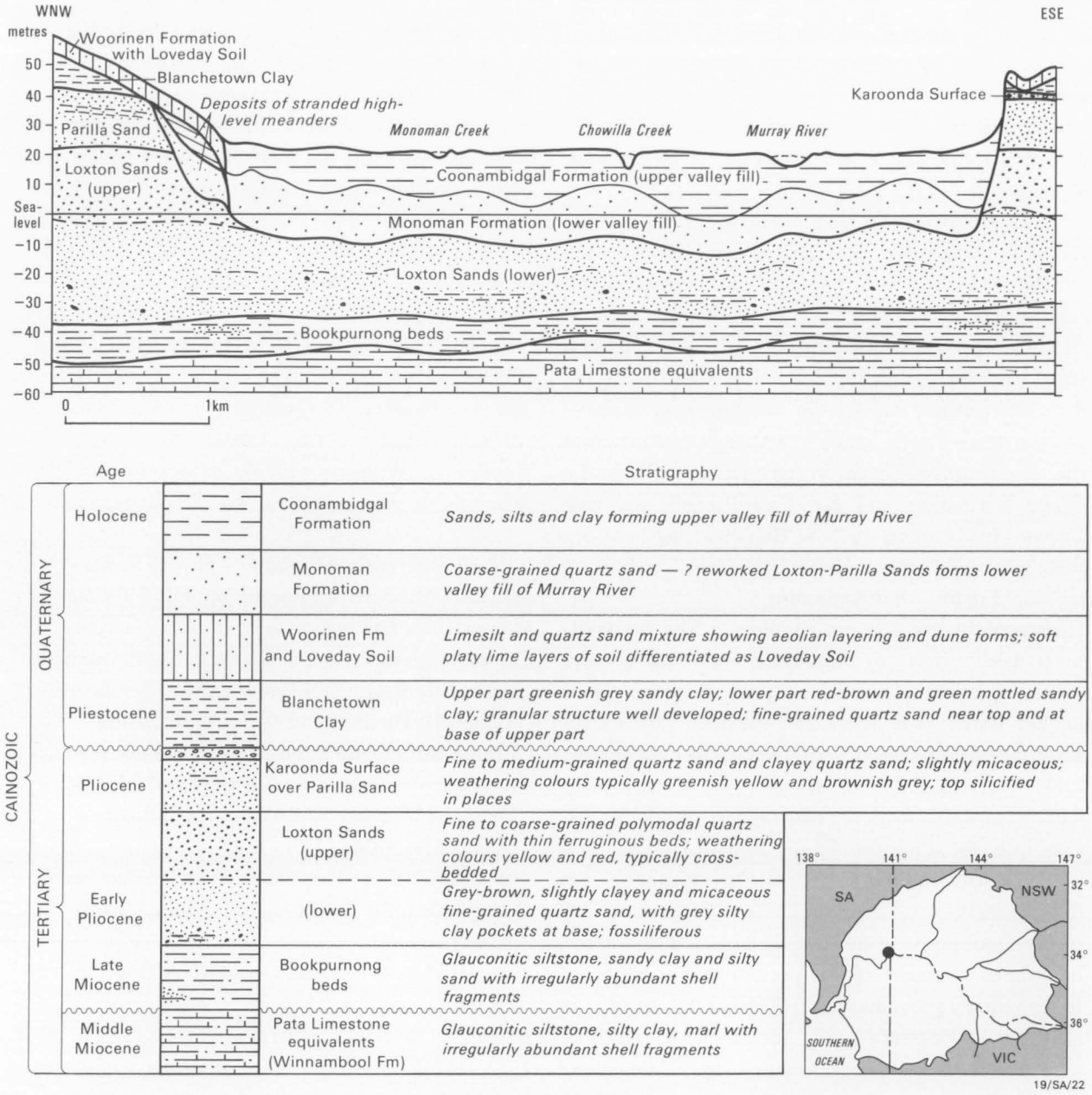


Fig. 87. Cross-section through axis of proposed Chowilla damsite; based on Firman (1973) with additional information from Ludbrook (1960) and Johnson & others (1960); description of stratigraphy of Chowilla area based on Firman (1966c).

the Loxton Sands the sediments are typically coarse-grained to gritty, micaceous and contain shell bands. Subsequently, Lawrence (1975) therefore correlated the Diapur Sandstone with the lithologically similar, fine-grained sands of the Parilla Sand of Firman (1965b) in South Australia, rather than with the Loxton Sands, and placed the entire Pliocene sand sequence in western Victoria in the Parilla Sand. Woolley & Williams (1978) then extended Lawrence's concept of Parilla Sand into New South Wales.

The Parilla Sand in western Victoria, unlike the defined unit in South Australia, contains marine fossils, including trace fossils, as well as estuarine faunas. In addition, in western Victoria, the upper surface of the Parilla Sand forms topographically subdued but slightly elevated, elongate, northwesterly trending ridges, whereas similar ridges were then unknown in areas adjacent to the Murray River in South Australia. The Parilla Sand of Lawrence (1975) in Victoria, therefore, does not readily correlate with the fluvial interpretation and definition of the Parilla Sand of Late Pliocene age of Firman (1965b). As discussed below, it seems likely that the

Fig. 88. Section at proposed Chowilla damsite (southeast CHOWILLA); uppermost unit consists of Woorinen Formation (Qdw) over calcrete, underlain by Blanchetown Clay (Qpc — light colored bands consist of silt), over ferruginised Karoonda Surface, underlain by Loxton–Parilla Sands (Tps).

bulk of the Parilla Sand in Victoria can be correlated with the marginal-marine to fluvial Loxton Sand, although clearly it almost certainly includes correlatives of the Parilla Sand of Firman (1965b). Differences in grain size and mineralogy between the Victorian 'Parilla Sand' and the South Australian Loxton Sands probably reflect differences in proximity to estuaries of the ancestral Murray and Darling river systems, as well as differences in provenance of sand sources, and water circulation patterns in the 'Murravian Gulf'. For example, if the ancestral Murray River entered the then 'Murravian Gulf' at its northeastern margin, then one might expect differences in grain size and mineralogy to both the northwest and southeast.

In order to overcome the above nomenclatural difficulties, in this Bulletin the Pliocene sand units are viewed as parts of a single composite sand sheet, deposited in a complex array of environments including shallow to marginal-marine, estuarine, and fluvial, and the upper surface of which formed a strandplain. For convenience we refer to this sand sheet as undifferentiated Loxton–Parilla Sands (Tps). It is anticipated that subsequent work may allow differentiation of the various components of the sand sheet. The Lower Pliocene 'Upper' and 'Lower' Loxton Sands (Table 25), Upper Pliocene Parilla Sand (Table 26), and Upper Pliocene Moorna Formation (Table 28) of Gill (1973a), are exposed in cliffs of the Murray River between Merbein (MILDURA) and Loxton (RENMARK), represent such subdivisions. At present, however, detailed differentiation of component units within the Loxton–Parilla Sands has only been achieved in the central-west of the basin, where extensive sections are exposed in the cliffs of the Murray River, and in the Gredgwin Ridge area (Table 27) in the south, where the unit is exposed in large road paving quarries and municipal dumps.

The units exposed by the Murray River in the central-west are dominated by the fluvial deposits of an ancestral Murray River, and therefore are probably not representative of those within the apparently littoral-dominated sequences to the southeast. The Loxton–Parilla Sands are described collectively below, and separate descriptions of the Loxton Sands and Parilla Sand, as originally defined in South Australia, are contained in Tables 25 and 26, respectively.

Lithology. Undifferentiated Loxton–Parilla Sands form a composite unit consisting of the Loxton Sands and Parilla Sand in South Australia and the correlative 'Parilla Sand' in Victoria and New South Wales. Lithologically, the unit consists of yellow-brown, fine to coarse, well-sorted quartz sand and sandstone, with minor clay, silt, and pebble conglomerate. Locally, the unit includes poorly sorted, micaceous, quartz sand and gravel. The sands are weakly cemented and friable to unconsolidated, and in places have trace fossils of marine shells and burrows. The clay content is generally less than 15%, but increases towards the base of the unit. Sand grains are mainly quartz with minor chert, feldspar and lithic clasts. The quartz grains are generally spherical and subrounded to rounded, and are mainly clear but are locally coated in a limonitic cement. Locally, the sands include up to 2% of disseminated heavy minerals, including zircon, tourmaline, ilmenite and rutile (Lawrence, 1966). Upper sections of the unit are yellow to reddish-brown and lower sections are grey and commonly pyritic. As discussed below, these colour changes possibly reflect fluctuations in the level of the watertable, although the grey parts are probably also due to an increase in silt and clay content with depth (Lawrence, 1966).

Vic. D.M. Olney No.1 (Fig. 50) encountered an upward-coarsening sequence, consisting of fine-grained sand at depth, grading to medium-grained sands towards the top (Lawrence, 1975). Exposures of Loxton–Parilla Sands ('Parilla Sand' in Victorian terminology) in quarries in the Gredgwin Ridge region in the south (Macumber, 1969) consist of cross-bedded, fine to coarse-grained sandstone and sandy grit, which is locally strongly micaceous, and lithologically similar to the Loxton Sands of Ludbrook (1961a) in South Australia (Macumber, 1983). Beneath the Lake Tyrrell region, an upper sequence of oxidised white, red, and yellow, fine to coarse-grained sand, silt, and thin clay bands overlies a lower zone of reduced dark grey to black pyritic sands and silts with wood fragments and finely disseminated organic matter.

Towards the top of the unit, the sands contain an interstitial white kaolinitic or gibbsitic matrix, locally capped by a sandy, pisolitic duricrust of ferricrete and silcrete cements. Lateritic profiles have been referred to as the Timboon Pedoderm (Gill, 1973b), and a ferricrete zone at the top of the unit, at the proposed Chowilla damsite (Figs 87, 88) was referred to the Karoonda Surface by Firman (1973). The surface consists mainly of small limonite-cemented pebbles and pisolites of sand, which form a lateritic podsol (Figs 87, 88, 89). Silcrete has been reported at Rocks Hole in the western Sunset Desert (Lawrence, 1975). The weathered lateritic profiles are up to 15 m thick. Beneath the upper metre or so of red-brown soil, the sands are mottled with yellow and red clay and well-developed peds. These grade down to a soft friable jointed sandstone, usually fractured by both fossil and recent rootlets. Below this upper zone of kaolinite–gibbsite–limonite cements, the sand grains are generally loose to weakly friable. The surface is thought to be mainly of pedogenic origin (Coaldrake, 1951; Blackburn & others, 1967), but in places some ferricrete surfaces may have been partly formed by ferruginisation of sands cemented by iron oxides deposited from groundwater (Macumber, 1983; and see 'Qly'). Interstitial kaolinite in the upper weathered profile may have also been deposited during periods of fluctuating water tables accompanying removal of pyrite and silica from the saturated zone and subsequent concentration in the upper mottled zone. Macumber (1983) suggested

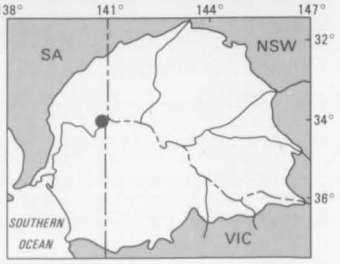


Fig. 89. Ferruginised Karoonda Surface, over Loxton–Parilla Sands at proposed Chowilla damsite (southeast CHOWILLA).

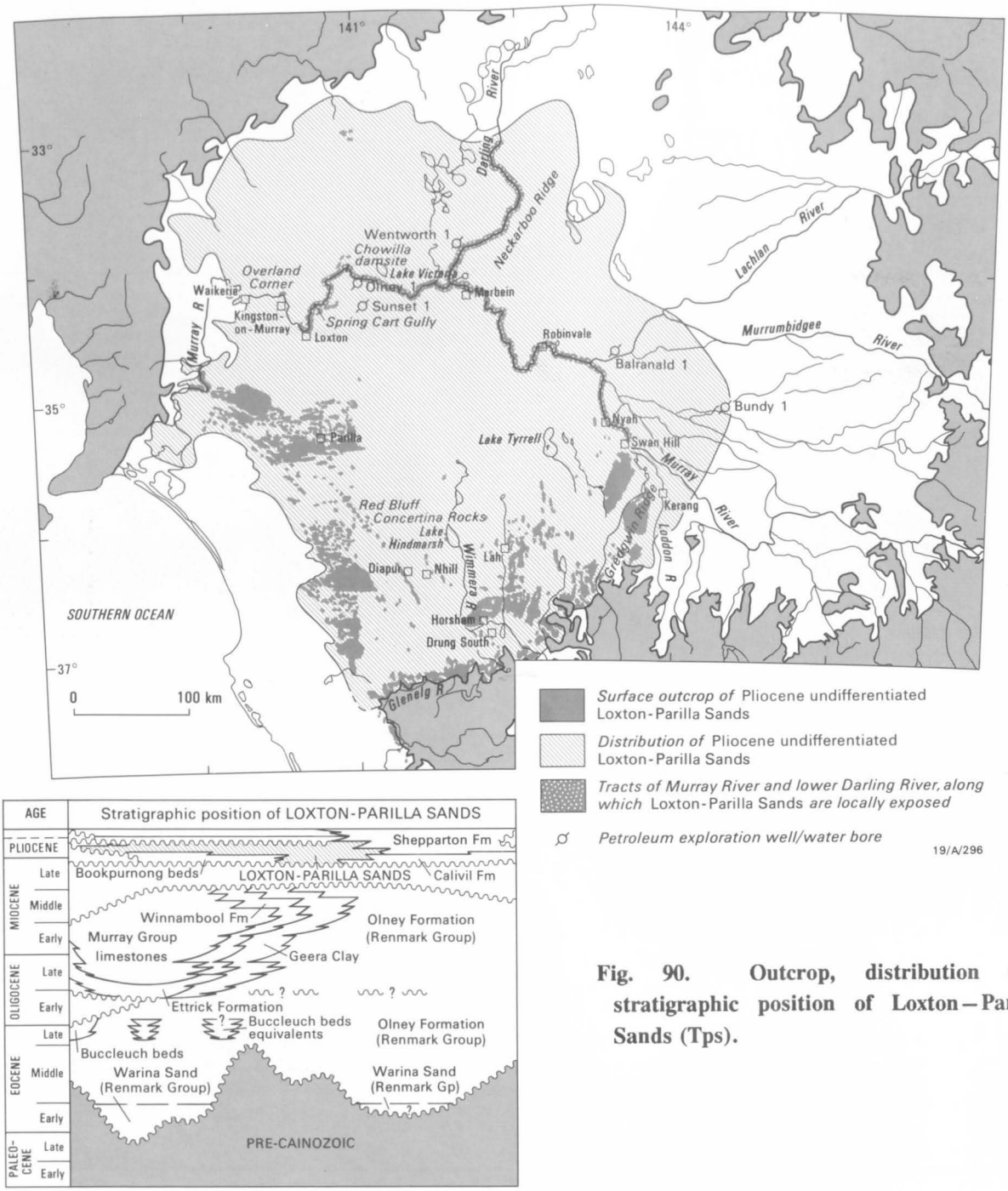


Fig. 90. Outcrop, distribution and stratigraphic position of Loxton–Parilla Sands (Tps).

that the presence of large quantities of iron in the unit is due to remobilisation of lateritic ironstones in recharge areas, followed by deposition from through-flowing groundwater.

Distribution and thickness. The Loxton–Parilla Sands have been encountered in several thousand boreholes, which indicate that the unit forms an extensive blanket of sand underlying much of the Mallee region (Lawrence, 1975, Brown & Stephenson, 1986), and extending beneath parts of the central-western Riverine Plain (e.g. Woodside Bundy No.1 in DENILIQUIN; Shiels, 1962) and the lower Loddon Valley (Macumber, 1978b). The unit is absent, however, from the western margin of the Pinnaroo Block, adjacent to the Murray River. Regional reconstructions suggest the unit was originally present over the southwest margin of the basin but was subsequently removed by marine erosion and aeolian deflation in the Quaternary (Fig. 90).

The blanket of sand has an average thickness of about 60 m in Victoria. The type section of the Loxton Sands component in South Australia is only 15.2 m thick (Ludbrook, 1961a). The type localities of the overlying fluvio-lacustrine Parilla Sand in South Australia are also generally only about 15 m thick (Firman, 1972). Considerably thicker sequences

Fig. 91. Photomosaic of Goroke 1:100 000 Sheet area, showing chains of small lakes (Ql, Qa) and Shepparton Formation (TQs), between north-northwesterly trending ridges of Loxton–Parilla Sands (Tps). Patches of dark vegetation along ridges are small blow-out dunefields of Molineaux–Lowan Sands (Qdm) resulting from local deflation of ridges of Loxton–Parilla Sands. Little Desert in north consists of irregular dunes of Molineaux–Lowan Sand.

TABLE 25. ?UPPER MIOCENE – LOWER PLIOCENE LOXTON SANDS (SOUTH AUSTRALIA)

Unit: Loxton Sands (South Australia)

Age: ?Late Miocene to Early Pliocene

Map symbol: included in Tps

Component units: Upper Loxton Sands, Lower Loxton Sands

Synonyms: Diapur Sandstone (Victoria)

Informal nomenclature: part of 'Undifferentiated Loxton – Parilla Sands', (and part equivalent to Parilla Sand in Victoria)

Lithology. In S.A. cross-bedded, micaceous sand, grit, and silty sand; characteristically bright yellow, or reddish to cream where weathered (Ludbrook, 1957, 1961a). Shelly bands usually present near base, and show secondary calcification (Ludbrook, 1957). Informally subdivided into upper and lower units by Firman (1972) and Rogers (1978, 1980a). Facies present within upper and lower zones differ somewhat with geographic location – in PINNAROO, Rogers (1980a) described lower zone as coastal facies, purplish-brown, medium to coarse-grained, calcareous, shelly, quartz sandstone. Grades to north (RENMARK) into, what Firman (1972) described as, estuarine facies of fine to medium-grained, calcareous, micaceous, shelly (near base), quartz sand. Farther north still (CHOWILLA), lower zone of grey-brown, clayey, fine-grained quartz sand (Rogers, 1978). Upper zones of Loxton Sands of fluvial and fluvio-lacustrine origin (Firman, 1972; Rogers, 1978, 1980a); consist of red, yellow, brownish quartz sand – micaceous except in north (Rogers, 1980a); fine to coarse-grained, although Rogers (1980a) records gravels in south. Loxton Sands normally poorly consolidated, but form cohesive sandstone near Waikerie and Cadell (Ludbrook, 1961a) on RENMARK.

Distribution and thickness. Loxton Sands recognised only in S.A. (in Victoria and N.S.W. same unit regarded as part of 'Parilla Sand'). Loxton Sands widespread in S.A., covering most of area of undifferentiated Loxton – Parilla Sands shown in Fig. 90. Unnamed Pliocene sand unit described by Cook & others (1977) in subsurface of Gambier Embayment may be either southerly extension of Loxton Sands, or distinct stratigraphic entity. Thickness of Loxton Sands highly variable, ranging from few metres to maximum 60 m (Rogers, 1978, 1980a; Brown & Stephenson, 1986) – partly as result of environments of deposition, partly due to local erosion in Late Pliocene during Parilla Sand deposition (about 3.5 Ma) and when Pinnaroo Block uplifted some 2.5 Ma (Stephenson, 1986), and partly during Quaternary deflation resulting in formation of Mallee dunefields.

Structure and topography. Partly deposited as stranded shallow-marine to littoral ridges (Brown, 1983, 1985) – visible today on air photographs (Fig. 91) and Landsat images (Figs 90, 92, 93). Ridges trend NW to southeast on PINNAROO and RENMARK (see 'Loxton – Parilla Sands'). In places, calcretes developed, particularly in ridges and swales, and acted as protective cap when ridge complex deflated – resulting calcrete-capped ridges seen at surface today (e.g. near townships of Wanbi and Alawoona, on RENMARK).

Palaeontology. Shallow-marine and littoral fauna dominated by molluscs (Fig. 95; Appendix 6); bryozoa also common, but some may be reworked from Miocene limestone (Ludbrook, 1961a). Base of Loxton Sands commonly more fossiliferous than top (but organic content at any particular locality depends upon local environment of deposition (shallow-marine, beach, back-beach dune, estuarine, fluvial) – with faunas becoming more impoverished to north and east). Microfauna (Ludbrook, 1961a) abundant to sparse. Both macrofauna and microfauna less varied and abundant in Loxton Sands than in related Bookpurnong beds.

Age evidence. Ludbrook (1961a) believed both Bookpurnong beds and Loxton Sands of Late Miocene – Early Pliocene age, but had no conclusive proof. Firman (1972, 1973) regarded both as Early Pliocene, whereas Rogers (1978, 1980a) thought Bookpurnong beds latest Miocene – Early Pliocene, and Loxton Sands Early Pliocene. Loxton Sands postdate Bookpurnong beds in S.A.; however, deposition of basal Loxton Sands farther north and east ('Parilla Sand' of Victoria and N.S.W. – see 'Loxton – Parilla Sands') began at same time as Bookpurnong beds; although regressive components of Loxton Sands younger than Bookpurnong beds. Bookpurnong beds dated Late Miocene – Early Pliocene ('Kalimnan'), and Loxton Sands overlain by Late Pliocene Norwest Bend Formation and Parilla Sand (both deposited before 2.5 Ma; Stephenson, 1986). Therefore, likely on stratigraphic grounds, Loxton Sands no younger than Early Pliocene, although contact between Loxton Sands and Parilla Sand must be diachronous, with 'beach ridges' progressively older towards east and north.

Characteristics. Loxton Sands recognised as separate formation only in S.A., where distinguished from Parilla Sand on basis of stratigraphic position, lithologic detail including fossil content, colour, clay and mica content (Parilla Sand more clayey; Loxton Sands more micaceous). Distinguished from younger sand units by lithology and stratigraphic position. May be confused with Pleistocene Bridgewater Formation, but latter more calcareous, and restricted to Gambier (Fig. 64) and Buccleuch Embayments (Fig. 55). Likewise, Early Pleistocene Coomandook Formation distinguished by stratigraphic and geographic position, although part of Loxton Sands lithologically similar.

Environment of deposition. Lower zone of Loxton Sands deposited in composite of shallow-marine, littoral, and beach-dune environments, during Late Miocene – Early Pliocene. Basal Loxton Sands in north deposited as sea-level rose between 6 – 4 Ma, although much greater volume of calcareous clays of Bookpurnong beds deposited at this time. Series of shallow-marine and beach ridges stranded during regressive phase of marine incursion. SW part of Murray Basin under marine and littoral conditions for longer than areas to north and east – reflected in sedimentology of lower zone. Upper sediments deposited during regression deposited in fluvio-lacustrine environments in most of S.A. Murray Basin (Firman, 1972; Rogers, 1978); fluvial environments over Pinnaroo Block (Rogers, 1980a). Deposited mainly over relatively short time interval within period 4 – 3.5 Ma – both upper part of Loxton Sands and all Parilla Sand deposited before 2.5 Ma (Stephenson, 1986).

Stratigraphic nomenclature and type section. Named after town of Loxton (RENMARK). Type section south of Loxton pumping station, Section 118, Hundred of Gordon (Ludbrook, 1957, 1961a). Sequence not completely exposed, and 15 m section of cross-bedded gritty sands and basal shelly beds may not be typical of range environments in which Loxton Sands deposited.

Stratigraphic relationships. Conformable over, and locally (in east and north) interfingers with Bookpurnong beds (Brown, 1983, 1985). Locally disconformable over both Pata and Morgan Limestones – disconformity represents late Middle to early Late Miocene hiatus. Parilla Sand locally conformably deposited between, and unconformably cross-cutting and entrenched within, stranded coastal ridges of Loxton Sands, giving appearance of entrenching and unconformable contact. In most places, boundary between Loxton Sands and younger Pliocene sands difficult to distinguish in bore logs. Disconformable to unconformable under Pleistocene units, including Blanchetown Clay, Woorinen and Pooraka Formations, and calcretes.

Hydrogeology and economic geology. Part of Pliocene Sands aquifer system (see Fig. 172 and 'Groundwater'). Quarried for concrete aggregate at Loxton (Ludbrook, 1961a) and other localities (Firman, 1972; Rogers, 1980a). Used as building stone at Waikerie and Cadell (Ludbrook, 1957; Firman, 1972).

Data sources. Ludbrook (1957, 1961a), Lawrence (1966, 1975), Firman (1972, 1973), Cook & others (1977), Lindsay (1977), Rogers (1978, 1980a), Brown (1983, 1985), Brown & Stephenson (1986), and Stephenson (1986).

TABLE 26. PLIOCENE PARILLA SAND (SOUTH AUSTRALIA)

Unit: Parilla Sand (South Australia)

Age: Late Pliocene

Map symbol: included in Tps

Synonyms: previously correlated with Diapur Sandstone (Victoria); part equivalent to 'Parilla Sand' (Victoria)

Informal nomenclature: part of 'Undifferentiated Loxton – Parilla Sands'

Lithology. In S.A. slightly clayey and micaceous quartz sand (Firman, 1966d, 1973); unconsolidated to weakly compacted and very friable; light grey, pale-brown, or pale-yellow; fine to medium-grained quartz dominant (Firman, 1972; Rogers, 1978, 1980a). Thin beds of olive sandy clay locally at top (Firman, 1972).

Distribution and thickness. Distribution poorly known (Fig. 90). Thickness in S.A. ranges from 30 m in east RENMARK (Firman, 1972), through average of 15 m elsewhere (Firman, 1972; Rogers, 1978, 1980a). Absent over some ridges of Loxton Sands. Forms cliffs of Murray River upstream from Loxton.

Palaeontology and age evidence. No palaeontological studies undertaken on Parilla Sand in S.A. – lithology and environment of deposition not conducive to fossil preservation. Age evidence based on stratigraphic relationships: overlies Early Pliocene Loxton Sands and interfingers with Norwest Bend Formation (with Pliocene fauna; Ludbrook, 1959). Boundary Loxton Sands and Parilla Sand diachronous, with contact progressively younger towards SW – Parilla Sand deposited over regressive phase of Loxton Sands as latter retreated. Regression thought to have occurred from about 4 Ma (Brown, 1983, 1985). Overlain by Blanchetown Clay (lowermost age no younger than 2.5 Ma – An Zhi–Sheng & others, 1986; Stephenson, 1986). In many places, ferruginous duricrust (Karoonda Surface/Soil) developed at top of Parilla Sand, prior to deposition of Blanchetown Clay (Rogers, 1980a). Above evidence suggests Parilla Sand ranges in age from about 4.0 to 2.8 Ma.

Characteristics. Lithology and stratigraphic position. Difficult to differentiate from underlying Loxton Sands, although break between two units apparent in some boreholes – Parilla Sand more clayey and less micaceous (in S.A.) than coarser-grained Loxton Sands, and unlike latter unit, does not have marine macrofossils. Parilla Sand differentiated from Norwest Bend Formation by absence of fossils in former and presence in latter.

Environment of deposition. Fluvial to fluvio-lacustrine non-marine environments (Firman, 1972, 1973; Rogers, 1980a). At Chowilla Dam Site (northeast RENMARK) shows fluvial sedimentary structures and cross-bedding. Rogers (1980a) noted old lake beds in Chandos area (PINNAROO). Partially formed by reworking of underlying Loxton Sands, and commonly deposited between stranded beach ridges of older formation, as well as by cross-cutting rivers, such as ancestral Murray, eroded into former strandline sands.

Stratigraphic nomenclature and type section. Named after township and Hundred of Parilla, County Chandos, S.A. Unit now known as Parilla Sand in S.A. originally regarded as part of Loxton Sands of Ludbrook (1957, 1961a). Name of Parilla Sand first published by Firman (1966a,d). Standard subsurface section in Parilla silo bore (No.7027–0511). Supplementary sections in Murray River cliffs, upstream from Bookpurnong (Firman, 1973). Type localities shown on maps of Pinnaroo area by Firman (1966a) and Rogers (1980a). Only partly correlates with 'Parilla Sand' in Victoria (which is equivalent mainly to Loxton Sands in S.A.).

Stratigraphic relationships. Conformable to disconformable over Lower Pliocene Loxton Sands, but may be disconformable to unconformable over Miocene sediments of Murray Group in north. Grades into Norwest Bend Formation near Kingston–on–Murray (Firman, 1966d), and these two units are partial time and facies equivalents (Firman, 1973), although Parilla Sand occurs over much larger area. Conformable to unconformable under Quaternary Blanchetown Clay, Woorinen Formation, Molineaux Sand, Yamba Formation, and recent alluvium (Qa). Near NW basin margins, Pooraka Formation may unconformably overlie Parilla Sand. Partly time-equivalent to fluvial Shepparton Formation, and may interfinger with that unit to east and north.

Hydrogeology and economic geology. Part of Pliocene Sands aquifer system (see 'Groundwater'). Groundwaters highly saline (e.g. north of Murray River – Rogers, 1978), but above water table in PINNAROO (Rogers, 1980a). Extensively quarried for road surfaces, and fine concrete aggregate (Rogers, 1978, 1980a; Firman, 1972).

Data sources. Parilla Sand (S.A.) described in Ludbrook (1957, 1961a), Firman (1966a, 1966d, 1972, 1973), Lawrence (1966), Rogers (1978, 1980a), Brown (1983, 1985), Brown & Stephenson (1985, 1986), Stephenson (1986).

of undifferentiated Loxton–Parilla Sands have been encountered in many boreholes farther to the south in South Australia, western New South Wales and northwest Victoria. For example, Woodside Balranald No.1 (Fig. 52) encountered a thickness of 70 m, A.O.G. Wentworth No.1 (Fig. 39) 73 m, and A.A.O. Sunset No.1 (Fig. 36) encountered 85 m. A water bore in PINNAROO (bore 6827-1101) encountered 108 m (Brown & Stephenson, 1986), and the thickest section recorded to date was an anomalously thick 120 m in a water bore in SWAN HILL (bore 933-8001; Tickell & Humphrys, 1979). Thickness variations possibly reflect local erosion/preservation of the original ridge and swale morphology of the upper surface (see below).

Outcrop and geomorphic expression. In Victoria, the unit is largely concealed beneath younger Quaternary sediments and aeolian landscapes. In western Victoria and adjacent areas of South Australia and southwest New South Wales, the near-surface components of the unit form partly buried, topographically subdued, but slightly elevated, sub-parallel, northwesterly and westerly trending ridges (Hills, 1939). Curvilinear sets of former littoral ridges and swales can be traced for several hundreds of kilometres. Individual ridges can be traced for up to 40 km, and are 2–3 km wide. Many ridges are truncated in the northwest by the Murray and Darling Rivers. Ridges with elevations of up to 60 m are locally preserved, but in general the upper surfaces of most of the ridges are deflated and are not now preserved. In the Horsham region, the locations of ridges and swales have mainly been defined by topographic ridges separated by elongate chains of small inter-ridge lakes (Figs 91, 92). Farther to the northwest, the ridges retain some topographic expression, but have been identified mainly from Landsat imagery. The sands are exposed at the surface over the uplifted Pinnaroo Block in southeast South Australia, but towards the southwest margin of

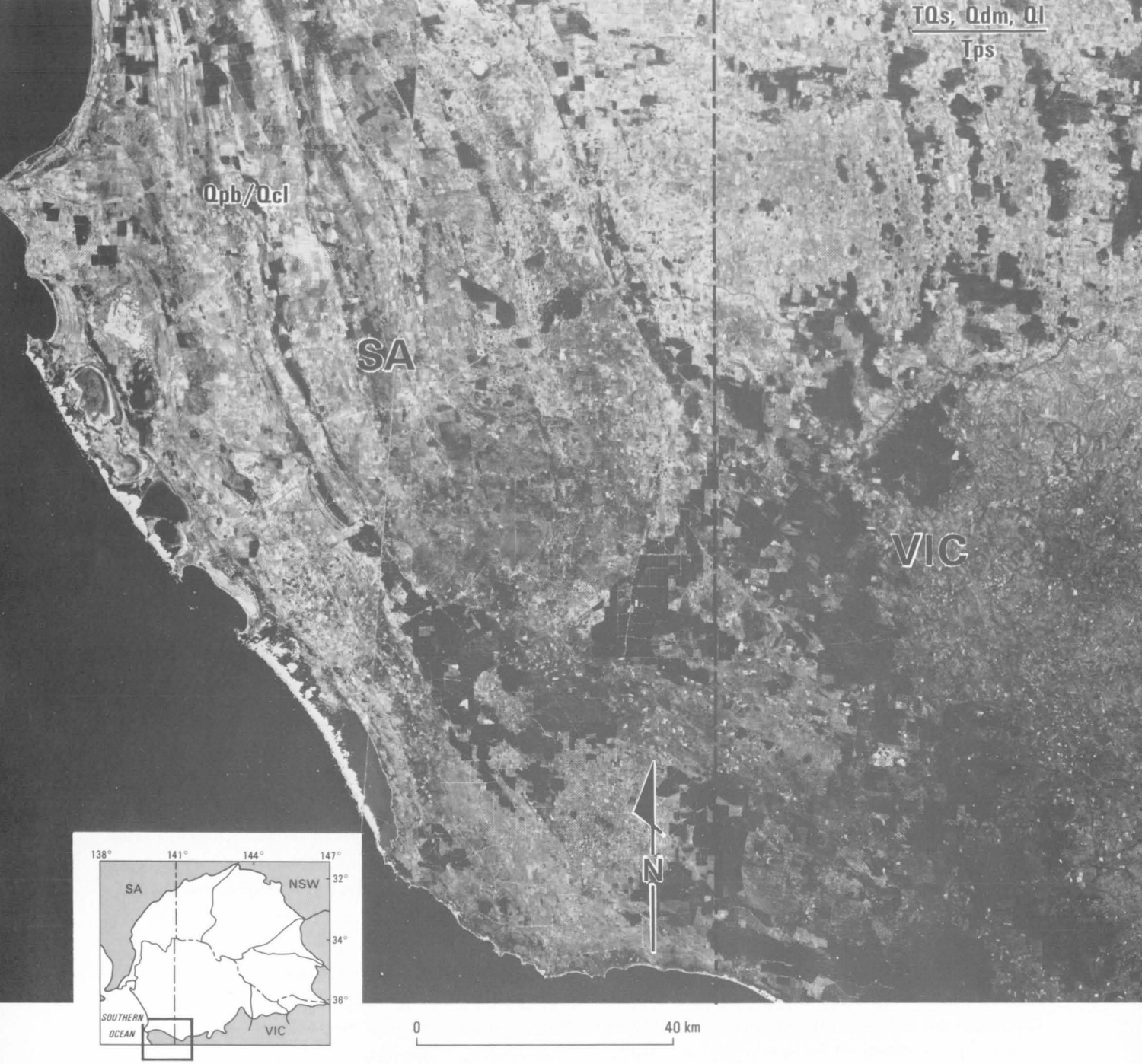


Fig. 92. Mount Gambier LANDSAT scene, showing stranded 'beach'-ridges and inter-ridge deposits of Pleistocene Bridgewater (Qpb) and Padthaway (Qcl) Formations in coastal areas of South Australia; as well as Shepparton Formation (TQs), Molineaux–Lowan Sands (Qdm), and lake deposits (Ql) over stranded shallow-marine and littoral deposits of Loxton–Parilla Sands in northeastern areas (in Victoria).

the basin, northeast of the Marmon Jabuk Range, many ridges have been entirely removed by aeolian erosion, and remnant traces of former ridge and swale sets are delineated by resistant calcrete ridges. These are thought to have partly formed at groundwater tables beneath the dunes and swales (Fig. 93).

In Victoria and New South Wales, the unit has mainly been examined in boreholes, but the ridge crests are locally exposed near Horsham (Figs 90, 91), and in river sections in the Glenelg and Wimmera Rivers. Blackburn & others (1967) produced a map showing the distribution of stranded beach ridges in the County Lowan area of western Victoria (between the Glenelg River on HAMILTON and the Big Desert on OUYEN). Outliers of fluvial components of the unit occur in the tributary valleys of the western highlands of Victoria. Exposures of the unit in southwest Victoria extend into adjacent areas of South Australia west of Nhill. Good exposures

also occur in quarries and road cuttings in the Gredgwin Ridge area west of Kerang on SWAN HILL. In addition, the unit is exposed at a number of localities in river cliff sections adjacent to the Murray River extending downstream from Nyah, near Swan Hill (northern Victoria) to Overland Corner (RENMARK) in South Australia (Fig. 94; Thorne & others, 1990). In western New South Wales, the unit is also locally exposed along sections of the lower Darling River (Fig. 96) and small outcrops occur in road cuts and paving pits in the adjacent Neckarboo Ridge of the Ivanhoe Block to the east. Elsewhere, deflation of the overlying aeolian sand has exposed the unit at Red Bluff (10 m section) and Concertina Rocks in the Big Desert (OUYEN). The unit also crops out at the western or southern margins of some lakes, such as Lake Victoria in southwestern New South Wales, and Lake Hindmarsh in Victoria.

The Karoonda Surface at the top of the unit is particularly well exposed at the proposed Chowilla dam site in RENMARK (Fig. 89; Firman, 1966c), and at a number of localities in the Mallee region. A similar extensive lateritised surface overlies the Parilla Sand equivalents (Dorodong Sand of Kenley, 1962, 1971) in the Dundas Plateau region in southwest Victoria (HAMILTON).

Internal geometry and log characteristics. In profile, individual topographic ridges of the Loxton–Parilla Sands are apparently symmetrical, but any original asymmetry is likely to have been destroyed by the post-depositional erosional and deflationary processes, which have resulted in the present subdued and rounded profiles. Internal structures in the friable sands are not preserved during drilling. In outcrop, they are often obscured by weathering and development of liesegang banding. Trough cross-bedded sands are exposed near Lah in HORSHAM (Lawrence, 1966), and cross-bedded sands exposed in a quarry 8 km west of Kerang (SWAN HILL) have been interpreted as offshore or beach deposits (Macumber, 1969, 1983).

On electric logs, the upper part of the unit, generally above the groundwater table, is characterised by high normal resistivity, whereas the underlying saturated zone is characterised by low normal resistivity (Lawrence, 1966). Gamma log profiles from fossiliferous sections in South Australia (Edwards, 1979, 1981a,b, 1982a,b, 1983) are not uncommonly smooth and funnel-shaped in profile, possibly reflecting the local presence of upward-coarsening sequences (e.g. Fig. 97). The presence of radioactive monazite in some of the heavy mineral bands encountered in Victoria is recorded as prominent peaks on Gamma logs (Macumber, 1983).

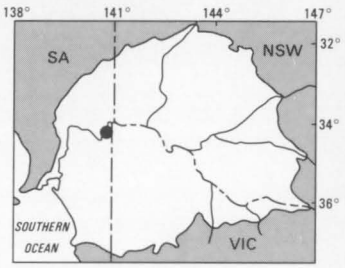
Palaeontology. The sands that form the dominant lithology of the unit are often highly porous and friable, and consequently few fossils are preserved within them. In most places, the original calcareous shells have been leached, and only fossil casts and moulds are now preserved in kaolin or limonite cemented sands. The shells include disarticulated pelecypod valves, and molluscs, such as *Dosinia* (*sensu lato*), *Garia*, *Tellina* sp. (Macumber, 1983). Plant materials, including leaves, have also been recorded. Many exposures along the banks of the Murray and lower Darling Rivers are characterised by bioturbation features, which have been identified as worm or crustacean burrows. Rare fossil wood fragments occur in upper parts of the sequence in western Victoria, and at one locality in the southwest of the Big Desert fossilised tree trunks have been reported (Lawrence, 1975).

The type section of the Loxton Sands (see Fig. 98) contains a molluscan fauna including *Donax depresa*, *Glycyneris cainozoica*, and *Nucularia* sp. (Ludbrook, 1961a). Ludbrook (1960) recorded rare to abundant foraminifera in the basal part of the Loxton Sands in bores at the proposed Chowilla damsite. In a series of bores drilled in the Victorian Mallee (OUYEN), Chapman (1916) identified estuarine, brackish water, and marine shells including foraminifera, spicules of calcisponges, echinoid spines and plates, and ostracods. Trace fossils of marine molluscs, bryozoans, and tellinid shells have been identified in quarries in the Stawell (Taylor, 1876) and Gredgwin Ridge (Macumber, 1978a) areas. Taylor (1876) described the marine molluscs *Lepralia stawellensis*, *Ditrupa normbeliensis*, *Tellina krausei*, *Nucla martae*, and *Turritella*. Similar assemblages were also identified in contiguous outcrops in the Glenelg River area in adjacent areas of the Otway Basin to the south of the basin. In Vic. D.M. Dimboola No.1 (HORSHAM), Crespin

Fig. 93. Mosaic of LANDSAT scenes from southwestern Murray Basin, showing 'ridge and swale' trend lines. Many apparent 'ridges' (e.g. Murray Bridge region) appear to consist of ridges of calcrete — one possible explanation is that these were deposited beneath former swales and ridges, from which Pliocene sands were removed by deflation to form the dunefields of the Molineaux–Lowan Sands (as well as dunes of the Woorinen Formation).

Renmark
Murray River Gorge
Traces of Pliocene
coastal ridges/swales
Murray Bridge
Lake Alexandrina
138°
141°
144°
147°
32°
34°
36°
SA
NSW
VIC
SOUTHERN
OCEAN
N

(a)



(b)

Fig. 94. (a) Loxton – Parilla Sands (Tps) under thin Blanchetown Clay (Qpc) and Bungunnia Limestone, exposed in aggregate quarry at Spring Cart Gully, east of Berri (northwest bank of Murray River, northeast RENMARK). (b) Cross-bedded Loxton – Parilla Sands within aggregate quarry shown in (a).

(1947) identified the estuarine foraminifera *Streblus beccarii* and *Elphidium crispium*. Lindsay (1965a) noted the presence of fish teeth in the Loxton Sands, and at Sunlands Pumping Station near Waikerie, Pledge (1985) subsequently described a diverse marine vertebrate fossil fauna with at least twelve species of shark, a ray, three species of teleoste, and four mammals including a whale. In addition, he identified a number of species of molluscs, bryozoa, crustaceans, echinoids, and gastropods.

Age evidence. Throughout much of their area of distribution, the Loxton – Parilla Sands conformably overlie marine sediments of the Bookpurnong beds, with 'Kalimnan' assemblages of Late Miocene to Early Pliocene age. Towards the eastern margins of the unit in Victoria, the basal components (e.g. transgressive Kerang Sand Member in Gredgwin Ridge area) appear to be partly equivalent to, and probably

interfinger with, the Bookpurnong beds. Palaeogeographic reconstructions of the Late Miocene, based on borehole data, indicate that a similar relationship exists beneath western N.S.W. and northern S.A., where the fluvial sands of the Calivil Formation are separated from the marine sediments of the Bookpurnong beds by a relatively narrow basal zone of Loxton–Parilla Sands (see cross-sections on SWAN HILL 1:250 000 geological map, and palaeogeographic reconstructions on Fig. 168).

Within the Loxton–Parilla Sands, impoverished assemblages mainly indicate only an approximate Pliocene or Early Pliocene age. The echinoid *Lovenia woodsi* of probable Late Miocene to Early Pliocene age has been identified in a quarry 11 km west of Kerang (Macumber, 1978a, 1983). In addition, the upper regressive member of the marginal-marine Loxton–Parilla Sands (Wandella Sandstone Member) has molluscan faunas of Pliocene age (Macumber, 1978a). Macrofossil and foraminiferal assemblages identified by Chapman (1916) and Ludbrook (1961a, 1963a) were also interpreted to be Pliocene in age. Chapman (1916) placed the unit in the 'Werrikooian Stage' of Hall & Pritchard (1902), which at that time was thought to be of Late Pliocene age, above the then entirely Early Pliocene, but now Late Miocene–Early Pliocene 'Kalimnan Stage'. Lithologically similar siliclastic sands disconformably underlie the calcareous Quaternary Bridgewater Formation of the Coorong, and in the Gambier Embayment, and have been dated as Pliocene (Cook & others, 1977). Firman (1966c) regarded the Loxton Sands in the west as Early Pliocene in age, and suggested that the overlying fluvial Parilla Sand (as defined in South Australia – see Table 26) is of Late Pliocene age, and partly equivalent to the Norwest Bend Formation, which was deposited during a slightly later, but minor, Late Pliocene marine transgressive–regressive pulse (Firman, 1972). Exposures at Boundary Bend are also thought to be of Late Pliocene age (Ludbrook, 1961a; Twidale & others, 1978). In the Murray River Gorge, near Kingston-on-Murray, fossiliferous estuarine oyster beds of the Norwest Bend Formation, which have been dated as ?Late Pliocene in age (Ludbrook, 1959, 1961a, 1963a), partly unconformably overlie older units and according to Firman (1973) partly grade laterally into the fluvio-lacustrine Parilla Sand – indicating that deposition of non-marine Parilla Sand probably occurred in the Late Pliocene. The Parilla Sand consists of fluvial channel sands which cross-cut, and are disconformably entrenched within, older components of the Loxton Sands (Firman, 1966c) – providing supporting evidence that the Loxton Sands are of no younger than Early Pliocene age, at least in inland sites.

At many localities, the Loxton–Parilla Sands are overlain by lateritic profiles, which at Chowilla dam site (Karoonda Surface) occur between the unit and overlying Blanchetown Clay. The presence of the upper lateritic zone suggests that a Late Pliocene period of weathering and non-deposition occurred, prior to deposition of the Blanchetown Clay. At Lake Tyrrell, the Loxton–Parilla Sands are overlain by Blanchetown Clay, which palaeomagnetic data indicates was first deposited within the Gilbert magnetic reversal spanning the Pliocene–Pleistocene boundary (Bowler, 1980; An Zhi-sheng & others, 1986; Stephenson, 1986). This provides an upper age limit within the Late Pliocene for deposition of the unit.

In summary, the regressive littoral components of the Loxton–Parilla Sands are dominantly of Early Pliocene age, although towards the eastern and northern limits of distribution of the unit, deposition of lateral equivalents of the Bookpurnong beds may have been initiated in the Late Miocene. Deposition of some younger components of estuarine, inter-ridge, cross-cutting and entrenched fluvial sediments probably continued into the Late

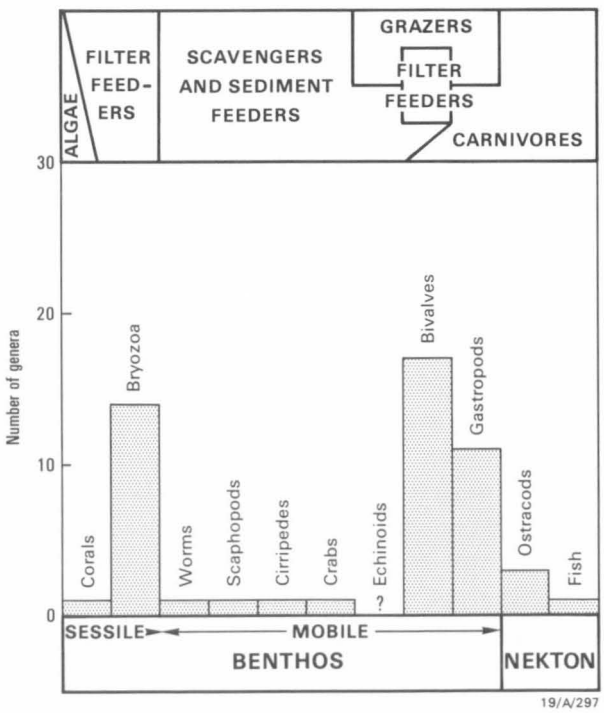
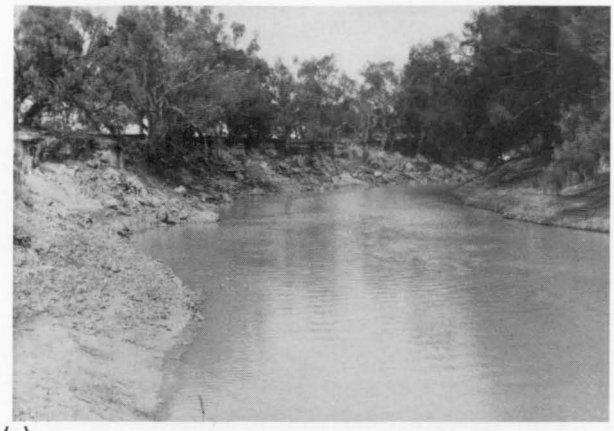
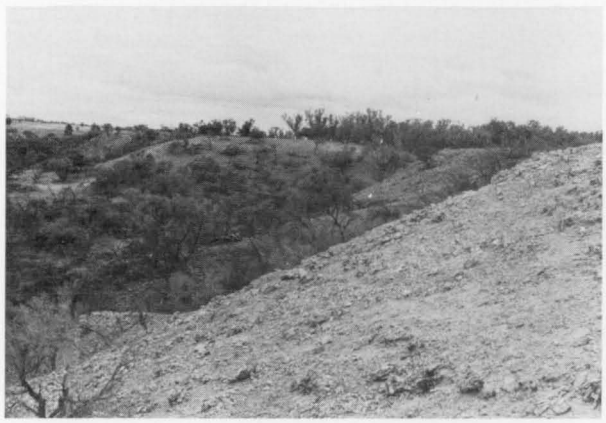


Fig. 95. Known macrofauna of Loxton–Parilla Sands (N.B. some bryozoan may be reworked from underlying Murray Group).



(a)



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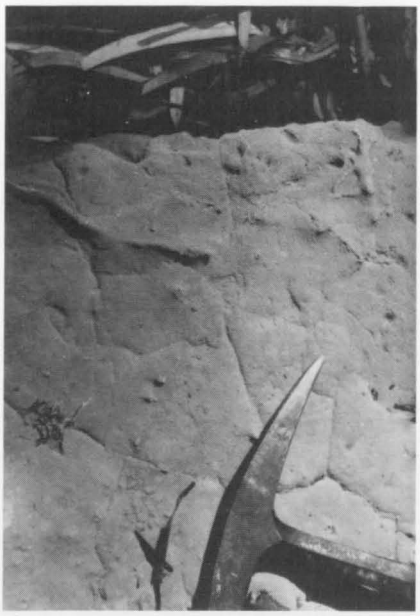

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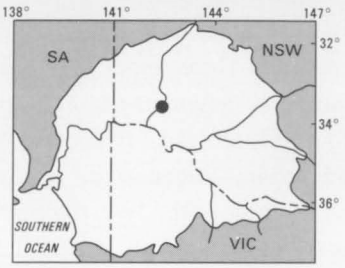


Fig. 96. Outcrop of Loxton–Parilla Sands (Tps) in southeast ANABRANCH – (a) exposed by Darling River near Lelma homestead; (b) stranded spurs of Loxton–Parilla Sands, representing former erosional level east of Darling River, above present-day floodplain; (c) horizontal trace fossils within Loxton–Parilla Sands.

Pliocene, but deposition of the unit was entirely pre-Quaternary.

Characteristics. Below the upper weathering surface the Loxton–Parilla Sands consist of clean quartz sand generally lacking in lithic clasts. The sand is commonly uncemented and free-flowing in boreholes, and in the absence of shell debris the marine components are difficult to differentiate from younger fluvial components. Some fluvial components consist of sand grains eroded from older marginal-marine components of the Loxton-Parilla Sands, and are therefore not necessarily petrographically distinct. The basal contact between the unit and the underlying Bookpurnong beds is marked by a downwards change from yellow or grey sands and silts to grey, fossiliferous glauconitic clays and silts. Descriptions of the Loxton Sands, Parilla Sand and sometimes Calivil Formation are frequently similar on drillers logs. The Calivil Formation, however, is generally buried beneath sediments of the Shepparton Formation, whereas the Loxton–Parilla Sands form a near-surface unit over which the Shepparton Formation is generally absent. In central-western areas in South Australia, the Loxton Sands are coarser-grained than the overlying fluvial sediments of the Parilla Sand, whereas in the south in Victoria Lawrence (1966, 1975) reported that the Loxton–Parilla Sands are upward coarsening. These differences probably reflect variations in depositional settings. As noted above, components of the Loxton–Parilla Sands can be differentiated in sections exposed by the Murray River at the western margins of the basin, and in the Gredgwin Ridge area in Victoria. Elsewhere, it is not yet possible to differentiate component units beneath the Mallee in Victoria and New South Wales.

Interpretation of environment of deposition. The northwesterly trending ridges of northwest Victoria were first identified by Hills (1939), who initially suggested that they may represent the surface expression

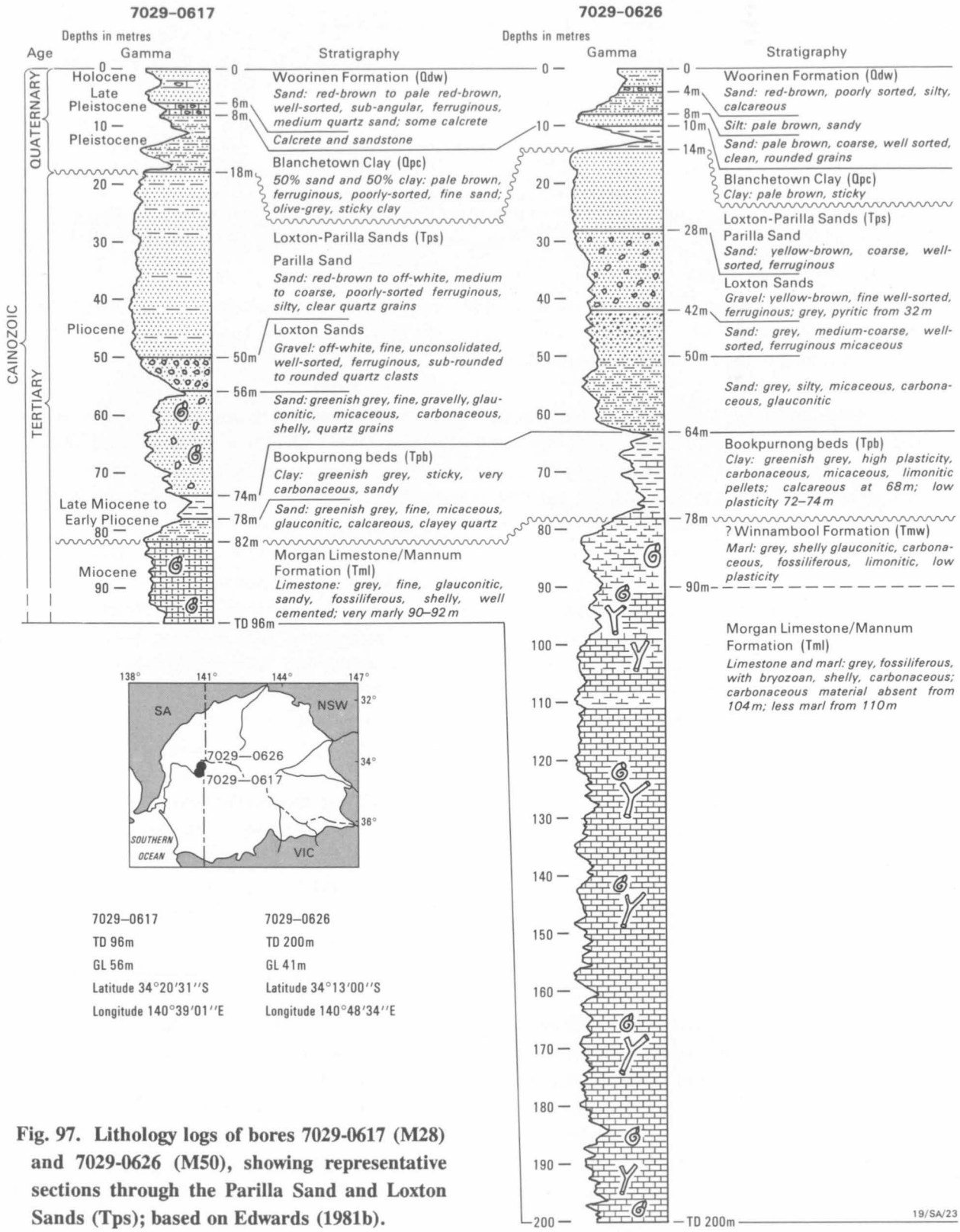


Fig. 97. Lithology logs of bores 7029-0617 (M28) and 7029-0626 (M50), showing representative sections through the Parilla Sand and Loxton Sands (Tps); based on Edwards (1981b).

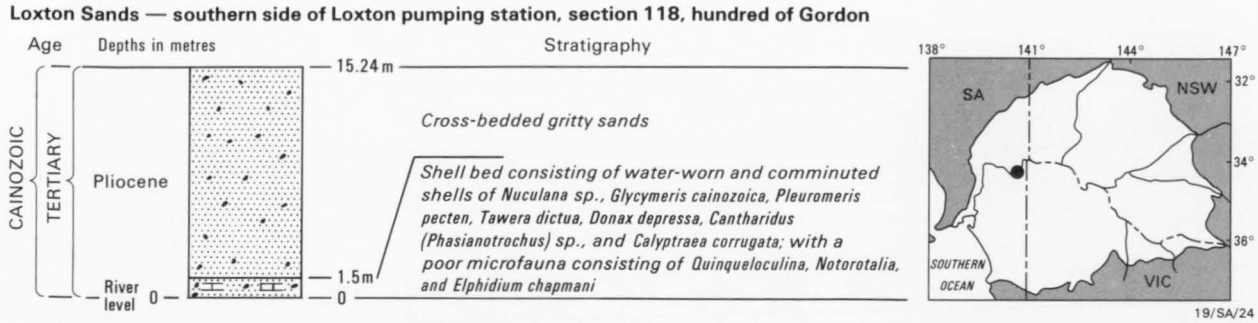


Fig. 98. Surface type section of Loxton Sands at Loxton Pumping Station (lithology and fossil content after Ludbrook, 1957, 1961a); only 15 m of section occurs above present-day river level, and consequently the section is not fully representative of the formation.

of underlying anticlinal folds in basement rocks. Based partly on an examination of Landsat mosaics, a number of arcuate northwesterly trending features have now been recognised in RENMARK and PINNAROO in South Australia, and in parts of western New South Wales, in addition to those previously recognised in western Victoria and coastal areas of South Australia (Hills, 1939; Blackburn, 1962a; Blackburn & others, 1965, 1967; Lawrence, 1966, 1975; Lawrence & Abele, 1976, 1988; Colwell, 1977; Macumber, 1978a; Jenkin, 1984; Brown, 1985, Brown & Stephenson, 1985; Carter, 1985). These lineaments are now interpreted as former shallow-marine and coastal ridges and swales. Blackburn (1962a) initially suggested that the ridges were deposited during intervals of high sea-level, and that they represent successive coastlines of a regressive Pliocene sea. He also noted that the ridges appear to demonstrate terminal curvatures adjacent to the flanking highlands to the south. He proposed that much of the sand content is aeolian in origin, and therefore suggested the deposits consist predominantly of stranded coastal dune complexes. Subsequent examination has indicated that the stranded ridges consist of a range of marginal-marine beach and offshore barrier-bar sediments, including inter-ridge estuarine and fluvial deposits, in addition to possible aeolian dune sands. In southwestern areas in South Australia, some of the lineaments appear to correlate with ridges or trends of thick calcrete, possibly deposited at former groundwater tables either within former ridges or beneath the intervening swales. In places, these present-day calcrete ridges possibly represent an inverted topography (Fig. 93).

Taylor (1875, 1876) recognised marine fossils in the Stawell area in highland valleys at the southern margin of the basin, but also identified deltaic and estuarine elements. In bores in the Mallee region, Chapman (1916) identified estuarine and shallow-water ostracods, sponge spicules and echinoid spines and plates, as well as undersized, thin-shelled foraminifera which he interpreted as being mainly estuarine, with some brackish-water and marine shells. He noted the local abundance of the temperate and shallow-water/estuarine foraminifera *Rotalia beccarii*. He also commented that in some bores the fossiliferous sands and silts are overlain either by non-fossiliferous quartz sands and grits or grey micaceous sands of variable thickness. As noted by Lawrence (1966), fossils are scarcer than might be predicted in the Loxton–Parilla Sands, but this probably reflects the highly porous nature of the sand which probably allowed fluctuating groundwater tables to leach out the carbonate. In general, the modern regional groundwaters of the Loxton-Parilla Sands are sufficiently acidic (Macumber, 1983) to dissolve carbonate shell debris. In some areas, the general decrease in grain size with depth (Lawrence, 1966, 1975) is consistent with deposition in regressive upward-coarsening shallow to marginal-marine and beach/barrier bar complexes. Local concentrations of disarticulated shell valves stacked convex down on bedding surfaces, in addition to the presence of bands of heavy mineral sands (Macumber, 1983), are also consistent with shallow-marine and beach deposits rather than aeolian dune deposits. Williams (in press) reported hummocky cross-stratification in Loxton–Parilla Sands in the south. Such structures suggest re-working of a shallow sea-floor by storm-generated waves.

The Loxton–Parilla Sands are mainly underlain by the Bookpurnong beds with apparent conformity, but laterally replace them to the east and north. It seems possible therefore that at the time of maxi-

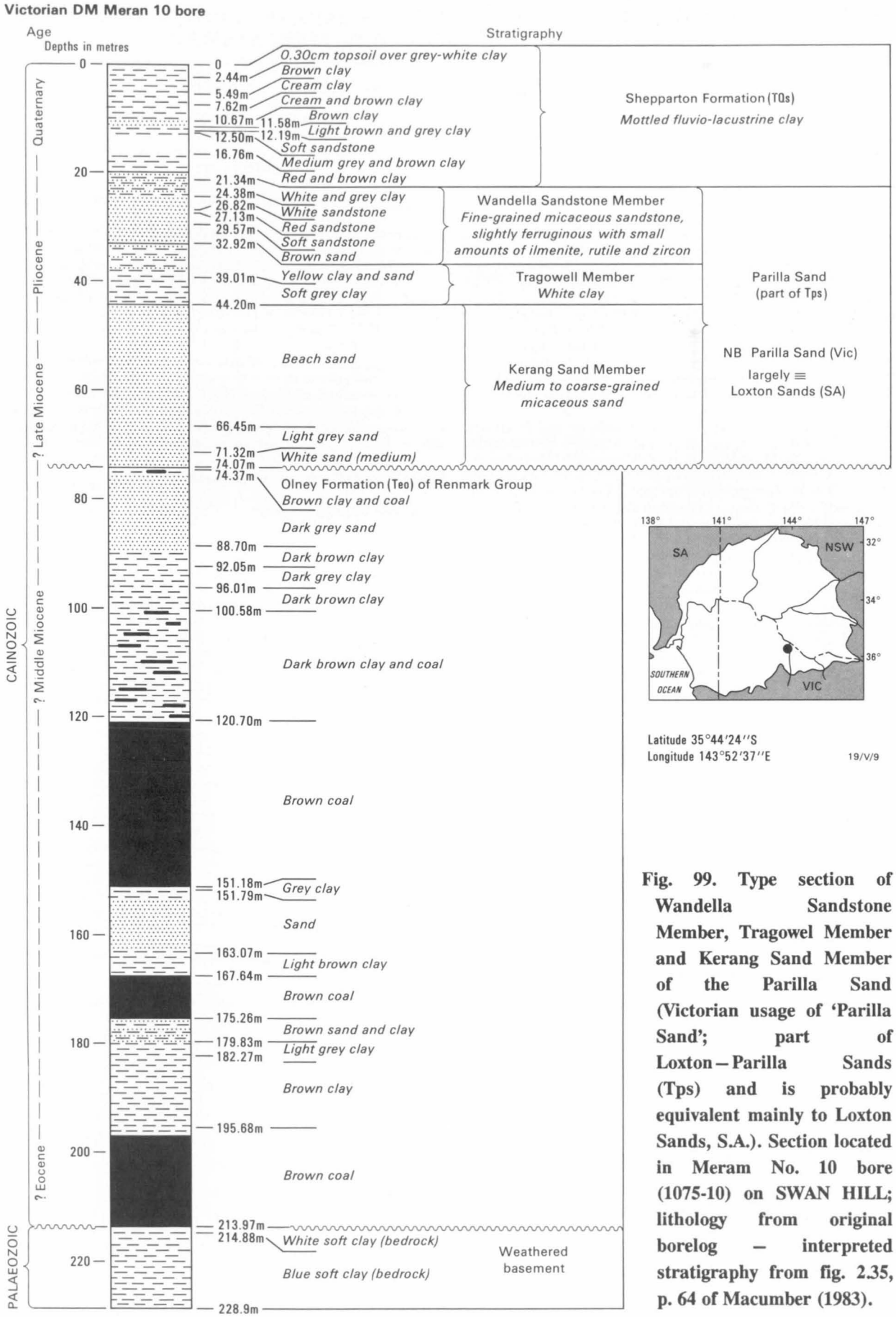


Fig. 99. Type section of Wandella Sandstone Member, Tragowel Member and Kerang Sand Member of the Parilla Sand (Victorian usage of 'Parilla Sand'; part of Loxton – Parilla Sands (Tps) and is probably equivalent mainly to Loxton Sands, S.A.). Section located in Meram No. 10 bore (1075-10) on SWAN HILL; lithology from original borelog – interpreted stratigraphy from fig. 2.35, p. 64 of Macumber (1983).

TABLE 27. ?UPPER MIOCENE – LOWER PLIOCENE KERANG SAND, TRAGOWEL, AND WANDELLA SANDSTONE MEMBERS OF THE LOXTON – PARILLA SANDS

Unit: Kerang Sand Member of Loxton – Parilla Sands

Age: ?Late Miocene – Early Pliocene

Map symbol: included in Tps

Lithology. Coarse-grained quartz sand in type area.
Distribution, thickness and outcrop. Member differentiated only in lower Loddon Valley and Gredgwin Ridge areas in south-central part of basin in Victoria (SWAN HILL). Maximum known thickness 30 m, type section 27 m. Encountered only in boreholes and not exposed at surface.
Palaeontology and age evidence. Rare marine fossils and fossil casts (including Lovenia woodsi; Macumber, 1978a). Intercalated with, and overlies, upper Calivil Formation, and also lateral equivalent of Bookpurnong beds, both of which are Late Miocene – Early Pliocene. Consequently, latest Miocene to Early Pliocene age indicated for Kerang Sand Member, partly on stratigraphic grounds and partly on fossil evidence.
Characteristics. Presence of marine fossils, as well as textural maturity of sand grains and differences in aquifer characteristics, allow Kerang Sand Member to be differentiated from sand and gravel of Calivil Formation (Macumber, 1983). Sand lithologies distinguish it from finer-grained sediments of Bookpurnong beds and Shepparton Formation. Lithologically similar to Wandella Sandstone Member, but separated from it by intervening fine sediments of Tragowel Member.
Environment of deposition. Thought to have been deposited in marginal to shallow-marine environments during marine transgression. Macumber (1983) suggested derived largely from re-worked material from underlying, and partly intercalated, Calivil Formation.
Stratigraphic nomenclature and type section. Named by Macumber (1978a) after Kerang (SWAN HILL). Macumber (1978b, 1983) nominated interval 47 – 74 m in Vic.D.M. Meram No.10 (bore 1075 – 10, 2 km west of Kerang) as type section (Fig. 99).
Stratigraphic relationships. Basal unit of Loxton – Parilla Sands in Victoria; conformable under Tragowel Member. Beneath lower Loddon Valley, conformable over, and in places intercalated with, upper Calivil Formation. Locally, disconformable over Olney Formation and unconformable over Palaeozoic metasedimentary basement rocks and granitoids. Bookpurnong beds absent from area, and subsurface cross-sections suggest probably lateral equivalent of, and intercalated with Bookpurnong beds to west – probably transitional between Bookpurnong beds and Calivil Formation.

Unit: Tragowel Member of Loxton – Parilla Sands

Age: Pliocene

Map symbol: included in Tps

Lithology. Mainly white clay and silt, but varies from light-grey to white, fine-grained quartz silt to silty claystone. Silts contain clear, transparent silt-size quartz grains in white clay matrix. To west, passes laterally into micaceous silty sand and sandy silt, with clay intercalations (Macumber, 1983).
Distribution, thickness and outcrop. Member differentiated only in boreholes beneath lower Loddon Plains and adjacent Gredgwin Ridge area in south-central part of basin in Victoria (SWAN HILL and ST. ARNAUD). Maximum known thickness 25 m, type section 14 m.
Age evidence. Based on stratigraphic position of Tragowel Member, likely age Early Pliocene.
Environment of deposition. Formed during period of marine transgression; deposited in near-shore, but deeper-water, marine environments, than marginal-marine underlying Kerang Sand and overlying Wandella Sandstone Members (Macumber, 1983).
Stratigraphic nomenclature and type section. Named by Macumber (1978b, 1983) after Parish of Tragowel few kilometres from Kerang (SWAN HILL). Type section between 33 – 47 m in Vic.D.M. Meram No.10 (bore 1075 – 10), 2 km west of Kerang (Fig. 99).
Stratigraphic relationships. Middle unit of three-fold subdivision of Loxton – Parilla Sands in central-south of Murray Basin. Type section conformable over Kerang Sand Member, and conformable under Wandella Sandstone Member. To east, laterally replaced by these units, and possibly lateral equivalent of basal Shepparton Formation. To west, probably lateral equivalent of Bookpurnong beds.

Unit: Wandella Sandstone Member of Loxton – Parilla Sands

Age: Pliocene

Map symbol: included in Tps

Lithology. Moderately cross-bedded micaceous sand and sandstone, minor sandy to granular conglomerate and pebble conglomerate. Minor bands of heavy minerals – in some bores, sufficiently concentrated to result in high count on Gamma logs.
Distribution, thickness and outcrop. Only differentiated in lower Loddon River and Gredgwin Ridge areas of central-south of basin in Victoria. Type section 13 m thick. Crops out at surface in Gredgwin Ridge (up-faulted area of undulating topography located west of lower Loddon River). Sands mainly concealed beneath thin blanket of Quaternary weathering profiles and loess, but exposed in quarries.
Palaeontology and age evidence. Rare marine fossils and fossil casts, but individual beds locally fossiliferous. Marine fossil shell debris thought to be Pliocene (Macumber, 1978a).
Environment of deposition. Sands interpreted as marginal-marine, including beach sands (Macumber, 1978a).
Stratigraphic nomenclature and type section. Named after Parish of Wandella few km from Kerang (SWAN HILL). Macumber (1983) nominated interval between 20 – 33 m in Vic.D.M. Meram No.10 (bore 1075 – 10, 2 km west of Kerang) as type section (Fig. 99).
Stratigraphic relationships. Uppermost member of Loxton – Parilla Sands in SE. Conformable over Tragowel Member. To east, subsurface cross-sections indicate lateral equivalent of, and locally overlain by, Shepparton Formation. Overlain mainly by Quaternary Woorinen Formation.

mum marine transgression, a genetic relationship existed between the two units, and that the basal Loxton – Parilla Sands in eastern and northern areas are littoral equivalents of the upper part of the shallow-marine Bookpurnong beds. The Loxton – Parilla Sands have often been interpreted as an entirely regressive sequence, but as described by Macumber (1978a, 1983) the basal component (Kerang Sand Member) in the east is transgressive over the fluvial Calivil Formation, whereas the upper component is a regressive shoreline sequence (Wandella Sandstone Member).

In South Australia, Ludbrook (1961a) suggested that sediments of the type section of the Loxton Sands were deposited in estuarine or shallow-marine environments. Firman (1966c, 1972) subsequently subdivided the Loxton Sands into the Lower Loxton Sands consisting of shallow-marine and estuarine sands, and the disconformably overlying Upper Loxton Sands consisting of fluvio-lacustrine sands. He also defined the overlying Upper Pliocene Parilla Sand as a younger, cross-cutting, entirely fluvial formation, partly entrenched within the Loxton Sands. In contrast, in Victoria and New South Wales, the

TABLE 28. UPPER PLIOCENE – LOWER PLEISTOCENE MOORNA FORMATION (SHEPPARTON FORMATION EQUIVALENT OF WESTERN MURRAY BASIN)

Unit: Moorna Formation

Age: Late Pliocene to ?Early Pleistocene

Map symbol: not differentiated from Tps, TQs on enclosed map

Lithology. Gill (1973a) described Moorna Formation as poorly sorted, current-bedded, light-grey to white gravel and coarse sand, grading to laminated clayey silt. Sand slightly micaceous, with rounded to angular clear quartz grains. Gravel includes pyrolusite and pebbles of dolomite.

Distribution and thickness. Identified by Gill (1973a) in number of cliff sections of Murray River, in NW Victoria and southwest N.S.W.; including measured sections on Moorna Station, and interpreted section at Merbein (MILDURA).

Palaeontology and age evidence. Fragmentary bones of fish, tortoise, bird egg shell, and marsupials; also worm casts, molluscs and ostracods (McKenzie & Gill, 1968). Extensive, well-preserved vertebrate fauna, with some of earliest known assemblages of Australian rodents – described in detail by Marshall (1973). Stratigraphic position above Loxton – Parilla Sands and beneath Blanchetown Clay suggests Late Pliocene to ?Early Pleistocene age, consistent with fossil fauna.

Environment of deposition. Interpreted as fluvial channel deposits.

Stratigraphic nomenclature and type section. Named by Gill (1973a) after Moorna Station adjacent to Murray River, 30 km southeast of Lake Victoria, in west N.S.W.. Type section at Fishermans Cliff on Moorna Station; up to 16.3 m of light grey to white silt to sand, including ossiferous gravelly sand (see Fig. 116 – based on figs. 1, 30 of Gill, 1973a). At Merbein on west bank of Murray River, at scenic lookout between winery and pumping station, Gill (1973a) recorded 17.9 m of white sand to fine gravel with current bedding – 1 m thick soft ironstone occurs towards base of cliff and boundary with overlying Chowilla Sand marked by presence of rhizomorphs under 60 cm of silicified sandstone – other authors, however, included this section in Loxton – Parilla Sands (see below).

Stratigraphic relationships. In type section area, disconformable under Blanchetown Clay and Chowilla Sand. Unlike Chowilla Sand, Moorna Formation always located beneath (and thus predates) Blanchetown Clay. Stratigraphically equivalent to Shepparton Formation farther east. May also represent differentiated late-stage component of otherwise undifferentiated Loxton – Parilla Sands – deposited in river channels incised into inter-ridge depressions (see 'Loxton – Parilla Sands'). Consists partly of re-worked sand and gravel. Not yet recognised in boreholes, and in absence of detailed examination surface exposures difficult to differentiate from Loxton – Parilla Sands – for this reason Moorna Formation exposed by Murray River included in Tps (or beneath TQs) on enclosed 1:1 000 000 geological map. N.B. – Firman (1971a) correlated 'Pliocene Sand' outcrops along Murray River, from the State border as far upstream as Nyah, with the Parilla Sand – a practice followed by most subsequent workers – whereas Gill (1973a), placed such sediments (with the exception of Chowilla Sand) along Murray River, in northern MILDURA, in Moorna Formation.

entire equivalent Pliocene sand unit was considered to consist of littoral sands, but was assigned to the Parilla Sand (Lawrence, 1975; Lawrence & Abele, 1976, 1988). Regional correlations, cross-sections and palaeogeographic reconstructions indicate that the 'Parilla Sand' in Victoria is mainly equivalent to the Loxton Sands, although inter-ridge fluvial sediments, some of which are probably equivalent to the Parilla Sand in South Australia are also present. In most drillers' borelogs, however, difficulties are experienced in differentiating these probable components and for the present, as noted above, they are viewed as components of a composite sand sheet, deposited in a complex of shallow-marine, littoral, and fluvial strandplain environments, and combined into a single Pliocene sand unit: undifferentiated Loxton – Parilla Sands (Tps).

Palaeogeographic reconstructions suggest that the unit was deposited largely during the regressive phase of a short-lived marine invasion of the western Murray Basin by a shallow epeiric sea variously referred to as the 'Murravian Gulf' or 'Murravian Sea' (Macumber, 1969). In places, the strandplain may include aeolian dune complexes of the type envisaged by Blackburn (1962a), but these have not generally been identified, and it seems likely that much of this material has been reworked by subsequent aeolian erosion. During the Late Quaternary, the near-surface Pliocene sands were subject to deflationary stripping, and were recycled to form the overlying Quaternary dunes of the Mallee region, as well as the dunefields and loess deposits of the eastern Murray Basin. In common with other reported occurrences of modern regressive strandline deposits elsewhere, the Pliocene strandplain sediments of the Murray Basin therefore appear to have poor preservation potential in the geologic record.

In summary, the undifferentiated Loxton – Parilla Sands form a composite sand sheet deposited in a complex of shelf to strandplain environments, including shallow-marine, beach/barrier bar and estuarine, flanked and locally overlain, and entrenched by inter-ridge and cross-cutting sands deposited in fluvio-lacustrine environments (Brown, 1983, 1985; Brown & Stephenson, 1985, 1986; see also block diagram on accompanying 1:1 000 000 geological map).

Stratigraphic nomenclature. The undifferentiated unit derives its name from the Loxton Sands (Table 25) and Parilla Sand (Table 26) in South Australia and the stratigraphically equivalent 'Parilla Sand' in Victoria.

Synonyms. The undifferentiated Loxton – Parilla Sands include the Pliocene Loxton Sands of Ludbrook (1957), Lower Pliocene Lower and Upper Loxton Sands, and Upper Pliocene Parilla Sand of Firman (1965a,b, 1966d, 1973) in South Australia. It

also includes the correlative Pliocene 'Parilla Sand' and earlier synonym Diapur Sandstone of Lawrence (1966, 1975) in Victoria and the equivalent 'Parilla Sand' of Woolley & Williams (1978) in New South Wales. In order to overcome this nomenclature confusion, the unit has frequently been informally referred to as the 'Pliocene Sands'.

Type sections. In Victoria, Lawrence (1966) nominated a railway cutting exposed in a northwesterly trending ridge located 4 km west of Diapur in HORSHAM as the type section of the synonymous 'Diapur Sandstone'. In South Australia, Ludbrook nominated a 15 m thick exposure on the southern side of Loxton pumping station, Section 118, Hundred of Gordon, as the type section of the Loxton Sands (see Table 25). The section consists of 13.5 m of cross-bedded, coarse, gritty, micaceous sands and silty sands, overlying a 1.5 m thick bed with water-worn and comminuted shell debris (Fig. 98). Firman (1965, 1966a, 1973) nominated investigation bores drilled at the site of the Parilla town silo as the type section of the Parilla Sand (Table 26). Firman (1973) also nominated sections exposed in cliffs of the Murray River, upstream from Bookpurnong as supplementary type localities. The unit is up to 15 m thick at these localities. Macumber (1978a, 1983) nominated the interval between 20 and 74 m in Meram-10 bore (Fig. 99) as the type section of component members of the Loxton–Parilla Sands ('Parilla Sands' in Victorian terminology) near Kerang on SWAN HILL (Kerang Sand, Tragowel and Wandella Sandstone Members – see Table 27).

Stratigraphic relationships. In the central-western Murray Basin, the Loxton–Parilla Sands grade down through a transitional zone into the conformably underlying Bookpurnong beds. However, in some boreholes (e.g. Vic. D.M. Warraquil No.3; Fig. 62) coarse sand and gravel components of the Loxton–Parilla Sands are thought to disconformably overlie the Bookpurnong beds at a sharp boundary (Lawrence, 1975). Towards its eastern and northern limits the Loxton–Parilla Sands appear to laterally replace the Bookpurnong beds, and basal components are therefore partly equivalent to that unit. The base of the Loxton–Parilla Sands is therefore partly diachronous. In the southwest and at the western margin of the basin, the Pliocene sand unit disconformably and, locally unconformably, onlaps the Morgan Limestone, Mannum Formation, Pata Limestone and Geera Clay. Beneath the northern, eastern, and southern limits of the unit, in the absence of the Bookpurnong beds (e.g. beneath the central-western Riverine Plain), it overlies with apparent conformity, and is intercalated with, coarse-grained sands and gravels of the fluvial Calivil Formation. In the lower Loddon Valley, for example, the Bookpurnong beds are entirely absent and the Loxton–Parilla Sands mainly overlie the fluvial Calivil Formation, but locally also unconformably overlies sediments of the Olney Formation and weathered Palaeozoic basement rocks (Macumber, 1978a,b,c, 1983).

In South Australia, the fluvial Upper Pliocene Parilla Sand conformably overlies and is locally entrenched within the Lower Pliocene Loxton Sands (Firman, 1966c, 1973; Ludbrook, 1969a). Near Kingston-on-Murray (RENMARK), the fluvial Parilla Sand grades laterally into estuarine oyster beds of the Upper Pliocene Norwest Bend Formation (Firman, 1966b; Carter, 1985). Towards the southwestern margin of the basin, the Pliocene sand unit was formerly thought to grade laterally into sediments of the topographically similar, but Quaternary, Bridgewater Formation. The Bridgewater Formation was therefore viewed as a younger regressive component of the Pliocene sand unit occurring farther inland. Foraminiferal investigations of core material collected during a drilling program undertaken to investigate the Bridgewater Formation (Cook & others, 1977) revealed, however, the presence of Pliocene sands disconformably underlying the Pleistocene unit, indicating that the Bridgewater Formation was deposited during younger transgressive–regressive cycles.

At the northern and eastern limits of the Loxton–Parilla Sands, upper components are laterally equivalent to, and are locally overlain by, fluvial sediments of the Shepparton Formation. Beneath the lower Loddon Valley, the unit is partly equivalent to, and partly overlain by, red and grey mottled clays of the Yando Clay Member of the Shepparton Formation (Macumber, 1983). Locally, in HORSHAM and NARACOORTE, fluvio-lacustrine Shepparton Formation or ?lagoonal–lacustrine equivalents are preserved in swales between ridges of Loxton–Parilla Sands. Over much of its area of distribution, the unit is capped by the weathered Karoonda Surface. Beneath central-western areas of the basin, the sands are disconformably blanketed by the Blanchetown Clay of ?latest Pliocene to Pleistocene age. In southern areas, and probably also beneath some northern areas, the Blanchetown Clay is restricted in distribution to the former swales, and is absent over intervening former ridges. In the absence of Blanchetown Clay, the Pliocene sand unit is unconformably overlain by Upper Pleistocene to Holocene

aeolian and lacustrine deposits, as well as by a number of lateritic, calcrete and silcrete duricrusts. Deflation of the Pliocene sand unit is thought to have provided the major source of sand for the dunefields of the disconformably overlying Woorinen Formation, and Molineaux–Lowan Sands.

Correlative units. In southwestern Victoria, the Loxton–Parilla Sands are contiguous with, and equivalent to, the Dorodong Sandstone (Kenley, 1962, 1971) of the Otway Basin sequence to the south.

Aquifer characteristics and economic geology. The Loxton–Parilla Sands form part of the Pliocene Sands aquifer system of the Murray Basin (see 'Groundwater'). The unit contains highly saline waters which locally surface in salt lakes. Salinity levels in the Murray River rise significantly in those stretches where the river is entrenched within the aquifer system. Bands of heavy minerals occur in the Gredgwin Ridge, Kerang and Horsham areas (Macumber, 1978a, Colwell, 1979). Several areas of the Pliocene strandplain are currently being investigated, and major deposits have been discovered in the Horsham area (see 'Heavy minerals').

Data sources. Descriptions of the Loxton Sands in South Australia (Table 25) are given in Ludbrook (1957, 1961a, 1969a; 1973); of the South Australian occurrences of the Parilla Sand (Table 26) in Firman (1965a,b, 1972, 1973) and Rogers (1978, 1980a); and of the Pliocene sand unit in Victoria in Taylor (1876), Chapman (1916), Hills (1939), Blackburn (1962a), Lawrence (1966, 1975), Blackburn & others (1967), Gill (1973a), Lawrence & Abele (1976, 1988), and Macumber (1978a; 1983). Stratigraphic relationships between some of the components of the Loxton–Parilla Sands are discussed in Carter (1985). A detailed study of the Loxton–Parilla Sands along the course of the Murray River, from Nyah in Victoria to the South Australian border (Thorne, 1987; Thorne & Hoxley, 1988) is nearing completion (Thorne & others, 1990).

Component units of the Loxton–Parilla Sands

Descriptions of the Loxton Sands and Parilla Sand as originally defined in South Australia are given in Tables 25 and 26, respectively. In Victoria, based on an examination of borehole and quarry sections in the lower Loddon Valley, the Kerang, and the Gredgwin Ridge regions of the southern Murray Basin (SWAN HILL and ST. ARNAUD), Macumber (1978a,b, 1983) identified three component members (Table 27) within the Pliocene sand unit. These consist of a basal transgressive marginal-marine sand unit (Kerang Sand Member), an intermediate deeper-water silt and clay unit (Tragowel Member), and an upper regressive marginal-marine sand unit (Wandella Sandstone Member). These members have not yet been identified elsewhere in the basin, but Macumber (1983) has noted that bores drilled in the Quambatook and Wycheproof areas in the lower Avoca Valley (SWAN HILL and ST. ARNAUD) encountered sequences similar to those of the Loddon Valley. Macumber (1983) has also suggested that a major siltstone bed exposed within the Loxton Sands in quarries adjacent to the south bank of the Murray River a few kilometres south of Berri (S.A.) is lithologically similar to, and can be correlated with, his Tragowel Member. The descriptions in Table 27 are based on those of Macumber (1978a,b, 1983). Based on an examination of outcrop along the Murray River, Gill (1973a) differentiated the Upper Pliocene–?Lower Pleistocene Moorna Formation (Table 28) from the Loxton–Parilla Sands. The unit has not yet been identified on bore logs beyond the type area exposed by the Murray River.

Unit: Norwest Bend Formation
Age: Late Pliocene
Map symbol: Tpn
Synonyms: 'Ramco Stone', 'Waikerie Freestone'

Lithology. The Norwest Bend Formation is a coquinoid calcarenite, dominantly composed of calcitic shells (mainly oysters), with a quartz sand matrix in places (Fig. 101). Depending upon the relative abundance of shell detritus, the Norwest Bend Formation grades from a sandy limestone to a calcareous sandstone. Where it is sandier, the Norwest Bend Formation is pale grey, brown, and yellow (Firman, 1972; Rogers, 1978), and is moderately well cemented; where it is richer in fossils (e.g. Waikerie area) the Norwest Bend Formation takes the form of a hard white sandy limestone, locally showing false bedding (Ludbrook, 1961a).

Distribution and thickness. The distribution of the Norwest Bend Formation is restricted to a narrow zone in the west of the Murray Basin, roughly east–west between Kingston-on-Murray and Morgan, and north–south between Morgan and Tailem Bend (Fig. 100). This distribution follows an ancient course of the Murray River (Ludbrook, 1961a), which was inundated during the Late Pliocene (Firman, 1972). Thicknesses of 1–2 m are common for Norwest

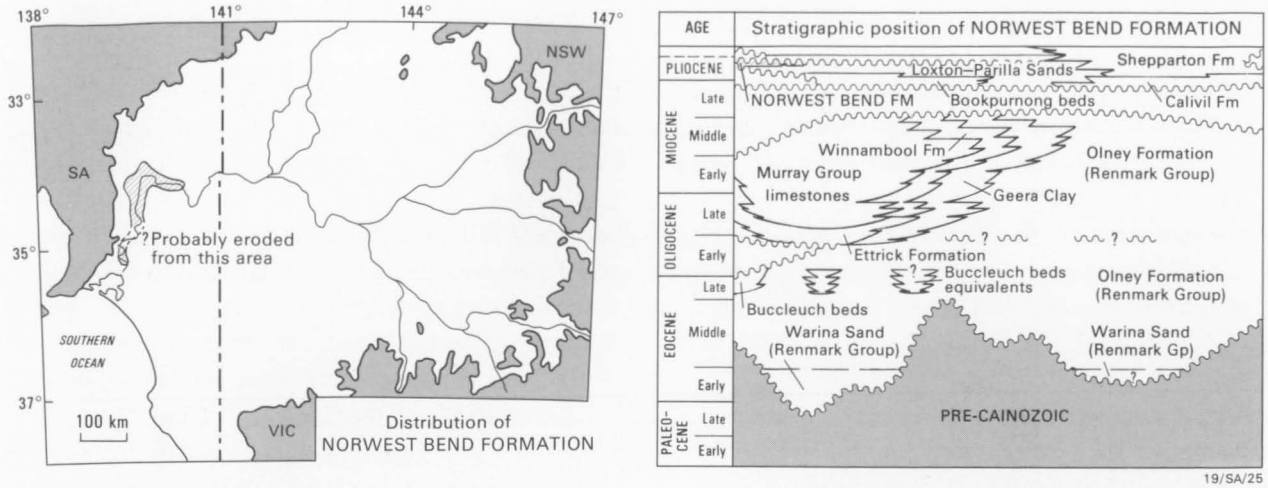


Fig. 100. Distribution and stratigraphic position of Norwest Bend Formation (Tpn).

Bend Formation, with 5 m being average, and 12 m the maximum. O'Driscoll (1960, p.186) described one bore near Tailem Bend as having encountered 34 m of Norwest Bend Formation, but this possibly includes underlying Morgan Limestone.

Geometry and topography. The Norwest Bend Formation usually presents a sheet-like appearance where exposed in the cliff-tops of the Murray River. Variations in its thickness are not abrupt, and it forms a resistant cap over softer sediments of the Murray Group limestones.

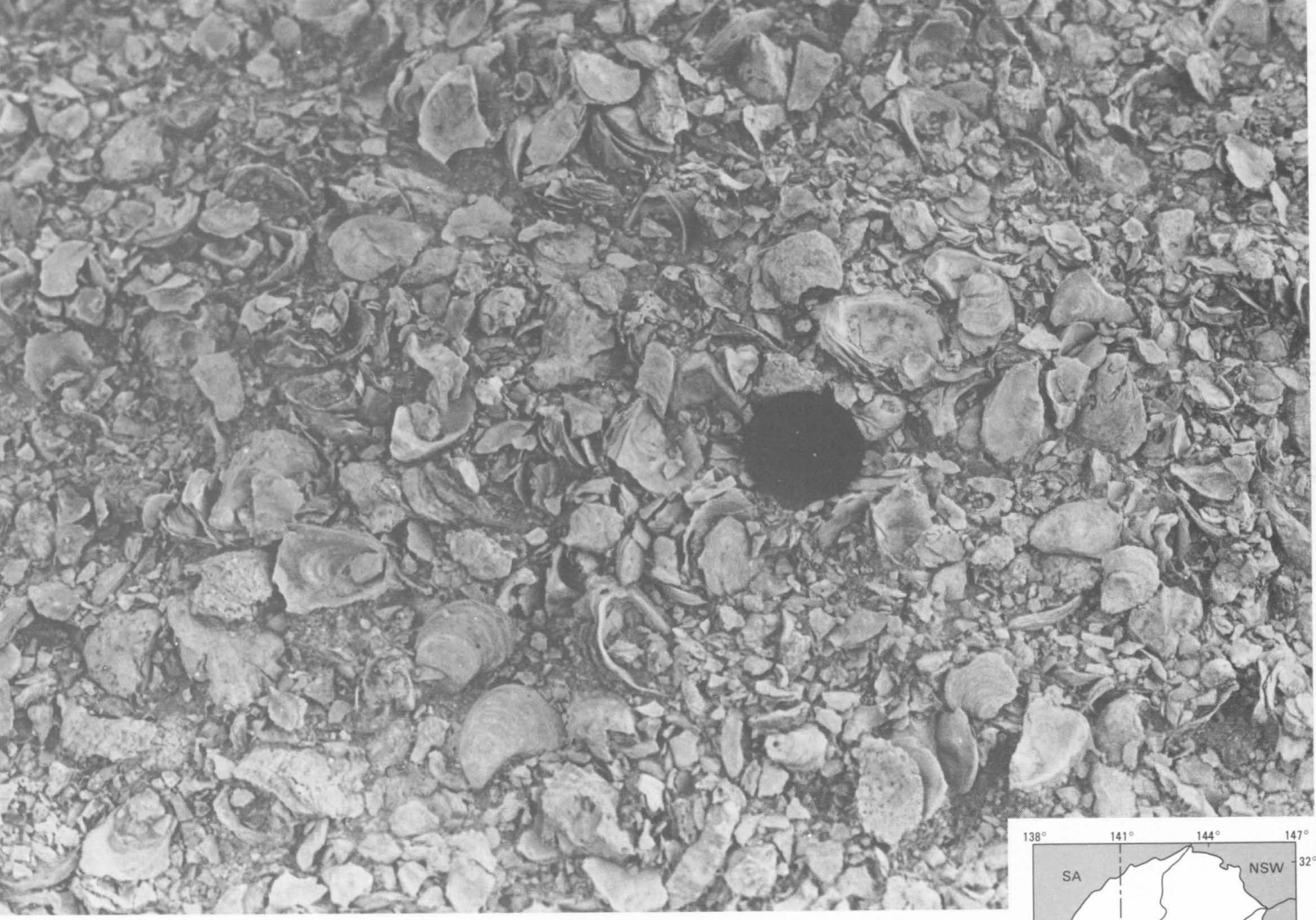
Palaeontology. Some 15 genera of bivalves were described from the Norwest Bend Formation by Ludbrook (1961a), but the fauna is dominated by the oyster *Ostrea*, which locally makes up over 90% by volume of the fossil material. Some oyster valves show evidence of algal borings, and many are encrusted by bryozoa or barnacles (Fig. 101). Less robust fossil forms are rarely preserved, although echinoids, scaphopods, branching corals, gastropod moulds, and shark teeth have been seen (unpublished data, A.E. Stephenson). The fauna indicates a high-energy estuary, with fossil diversity further limited by a mobile substrate and salinity variations. Foraminifera are sparse, and have been described by Lindsay & Bonnett (1973), but are almost entirely benthonic.

Age evidence. Ludbrook (1959) dated the Norwest Bend Formation as Pliocene, citing molluscs as evidence; on stratigraphic evidence she later refined this age to Late Pliocene (Ludbrook, 1963a), as the Norwest Bend Formation locally disconformably overlies the Lower Pliocene Loxton Sands. Lindsay & Bonnett (1973) also regarded the Norwest Bend Formation as having been deposited during the Late Pliocene, but did not give any additional evidence for this: the benthonic foraminifera are of limited biostratigraphic value. Much of the area of distribution of the Norwest Bend Formation was covered by Lake Bungunnia about 2.5 Ma ago (Stephenson, 1986), which would suggest that the estuarine deposits are no younger than about 2.8 Ma plus or minus 0.2 Ma (see 'Blanchetown Clay').

Characteristics. The primary characteristic of the Norwest Bend Formation is its abundance of oyster beds forming shell banks; its secondary characteristics are geographic and stratigraphic position. The Norwest Bend Formation grades laterally into the Parilla Sand, with virtually no fossils, and although there are transitional zones, the two end-member formations are differentiated by fossil content. The geographic position of the Norwest Bend Formation is an important characteristic, but not all of the thick oyster beds of the Murray Basin's western margins necessarily belong to that formation. Ludbrook (1961a) recorded oyster beds within the Early Pliocene Loxton Sands, and Recent oyster beds occur in the estuarine St Kilda Formation around Lake Alexandrina; these oyster beds can be distinguished from those of the Norwest Bend Formation by their stratigraphic and geographic positions.

Environment of deposition. Ludbrook (1961a) interpreted the Norwest Bend Formation as indicating the existence of a narrow Pliocene estuary roughly following the present course of the Murray River. Firman (1972) thought that a minor downwarp in the late Pliocene led to marine ingression and deposition of the estuarine Norwest Bend Formation; and Lindsay & Bonnett (1973) stated that the palaeontological evidence supported deposition in a shallow restricted-marine gulf.

The general consensus seems to be that the Nor-



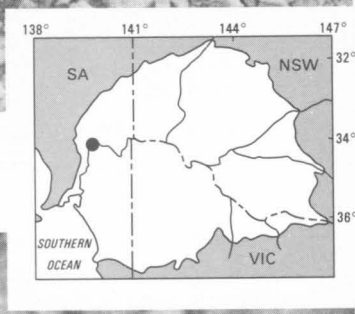


Fig. 101. Coquinoid limestone of Norwest Bend Formation – consisting of smashed oyster shell beds with minor other shell debris (see 'Palaeontology'); exposed at Morgan 'town dump' (northwest RENMARK).

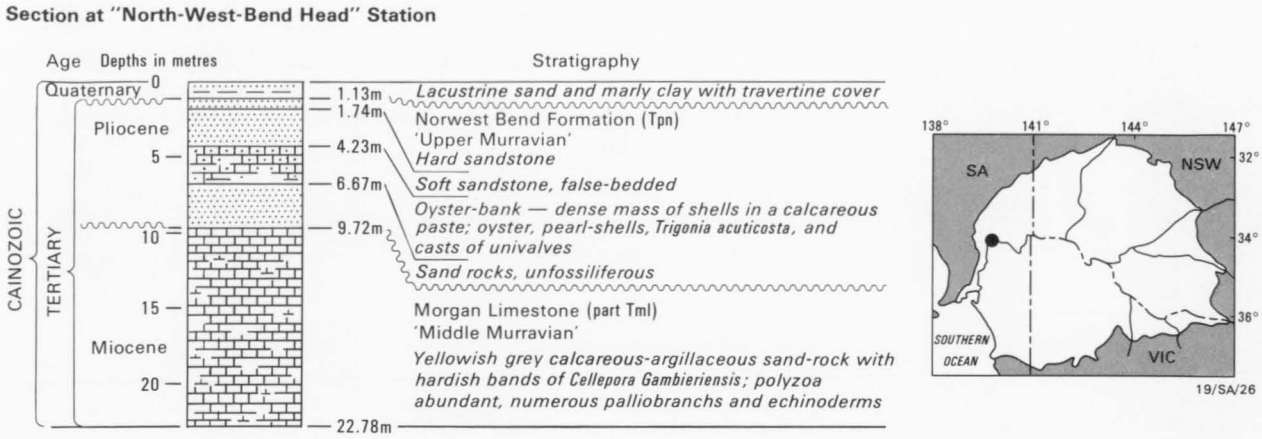


Fig. 102. Description of type section of Norwest Bend Formation from Tate (1885) — located at Norwest Bend Station, on major bend of Murray River, east of Morgan. Tate (1885) also noted that "eastwards of section, oyster-bed thickens, and at a mile (1.6 km) from Station, section consists of about 40 ft (12 m) of oysters and 29 ft (6.1 m) of yellow calciferous sand-rock".

west Bend Formation was deposited in a drowned valley of the ancestral Pliocene Murray River. The nature of the fauna and associated clastic sediments suggests the following environmental features:

- a high-energy environment of constantly shifting sand bars, with probably a strong tidal influence; and
- an ecosystem tolerant of variable salinities, dependent upon relative river flow rates and tidal factors.

Few benthic estuarine animals can thrive in such an environment: the oyster is an exception. Nevertheless, mortality rates would be high, and in fact most of the coquinas examined (unpublished data, A.E. Stephenson) appear to be taphrocoenoses (death assemblages, of Schafer, 1962), rather than the remains of organisms which died *in situ*.

Ludbrook (1959, 1963a) correlated the Norwest Bend Formation with various other rock units in the area of Gulf St. Vincent and Spencer Gulf (see below), and regarded these as being deposited during the same Late Pliocene marine transgression.

Stratigraphic nomenclature and type section. The Norwest Bend Formation is named after the station now known as 'Norwest Bend Station', near the 'North West Bend' of the Murray River north of the town of Morgan, South Australia. Structural constraints here cause the river to change its predominantly westwards course to southward, down to the Southern Ocean. The Norwest Bend Formation is particularly well developed in this area, and forms prominent cappings to the Murray River cliffs.

The type section was described by Tate (1885) at 'North-West-Bend Head Station'. Since then, the names of the station and the actual river bend have evolved to the modern usages given above, and Ludbrook (1957, 1961a) followed the modern name of the station when formalizing the formation nomenclature. At the type section (Fig. 102), 8.6 m of sandy limestone, with the genera *Ostrea*, *Glycymeris*, *Donax*, and *Neotrigonia*, overlies 13.0 m of the Morgan Limestone (Tate, 1885; Ludbrook, 1961a).

Stratigraphic relationships. The Norwest Bend Formation normally disconformably overlies the Murray Group limestones (Mannum Formation, Morgan Limestone, and probably Pata Limestone), or it conformably to disconformably overlies the Loxton Sands where the latter unit is present. The Parilla Sand is a partial time and facies equivalent of the Norwest Bend Formation, and the two formations grade into each other near Kingston-on-Murray (Firman, 1966d). The formation is disconformably overlain by several Quaternary units, including the fluvio-lacustrine Blanchetown Clay, lacustrine Bungunnia Limestone, aeolian Woorinen Formation, Molineaux Sand, and Bunyip Sand, Pleistocene outwash deposits of the Pooraka Formation, various calcretes (Qca), and recent alluvium of streams and the Murray River overbank deposits (Qa). Even in outcrops at the top of the Murray River cliffs, the Norwest Bend Formation is normally covered by a veneer of aeolian material.

Correlations. Within the Murray Basin, the Norwest Bend Formation is a partial time and facies equivalent of the Parilla Sand (as defined in South Australia, Table 26). Ludbrook (1959, 1963a) also correlated the Norwest Bend Formation with the following units in other basins: (a) the Hallett Cove

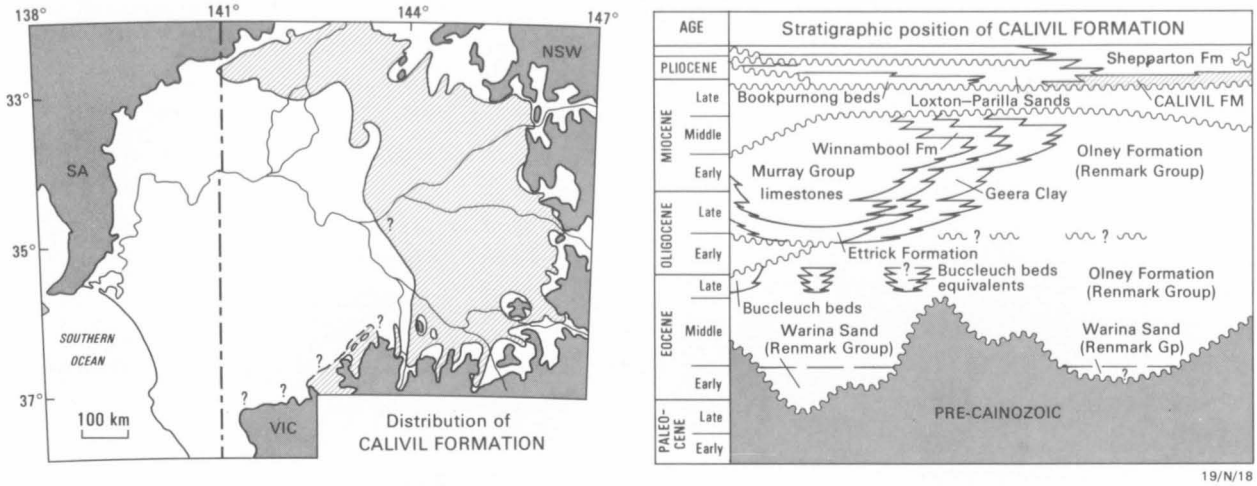


Fig. 103. Distribution and stratigraphic position of Calivil Formation (Tpc).

Sandstone of the Willunga Embayment, the Noarlunga Embayment, and the Adelaide Plains Basin; (b) the Dry Creek Sands of the Adelaide Plains Basin; (c) the Wallaroo Formation and the Edithburg Formation of Yorke Peninsula; (d) the Fishing Bay Formation and the Deep Creek Formation of Eyre Peninsula; and (e) the Gum Creek Formation and the Point Reynolds Formation of Kangaroo Island.

Hydrogeology and economic geology. The Norwest Bend Formation is contiguous with the Pliocene Sands aquifer system, but in the area where it occurs, over the up-faulted Pinnaroo Block, it is generally above the modern regional groundwater table, although minor perched aquifers may occur locally. The formation has, in the past, been used as building stone, under the local names 'Ramco Stone' and 'Waikerie Freestone' (Ludbrook, 1961a); it has also been used as road aggregate.

Data sources. The Norwest Bend Formation is described in publications by Tate (1885), Ludbrook (1957, 1959, 1961a, 1963a), O'Driscoll (1960), Firman (1966d, 1972), Lindsay & Bonnett (1973), Rogers (1978), and Brown & Stephenson (1986).

Unit: Wunghnu Group
Age: Late Miocene to Quaternary
Component formations: Calivil Formation (Tpc) – Late Miocene to Pliocene in age; Torrumbarry Clay – mainly Late Miocene to Pliocene in age (Table 29); Shepparton Formation – Pliocene to Quaternary in age; Coonambidgal Formation and other Upper Pleistocene to Holocene alluvial deposits (see Chapter 10)

Definition. The Wunghnu Group consists of thick Upper Miocene to Recent continental sediments, which were deposited mainly over the eastern and northern Murray Basin, and which can be subdivided into several formations. As defined by Lawrence (1966, 1975), these formations occupy the stratigraphic interval of non-marine sediments between the top of the Olney Formation (Renmark Group) and the present-day land surface. They are lithologically similar to the underlying non-marine Eocene and Miocene sediments of the Olney Formation, but are comparatively poor in carbonaceous material. Minor thin Quaternary fluvio-lacustrine sediments also occur in the west, but, with the exception of the Blanchetown Clay, these are confined in distribution to areas adjacent to the major modern river systems.

Lawrence (1966) named the Wunghnu Group after the township of Wunghnu, 25 km north of Shepparton in BENDIGO. The interval between the ground surface and 121 m in the Vic. D.M. Mundoona No.1 borehole (bore 1205-1), located 0.5 km southwest of Wunghnu, was nominated as the type section.

Unit: Calivil Formation of the Wunghnu Group
Age: Late Miocene to Pliocene (mainly Pliocene)
Map symbol: Tpc
Synonyms: Calivil Sand, 'Bookpurnong Beds Equivalents'
Associated unit: Torrumbarry Clay (Table 29)

Lithology. At the margins of the Murray Basin, the Calivil Formation consists mainly of pale grey, coarse to granular quartz sand and conglomerate, with a white sandy and silty clay matrix. Locally, the formation includes thick intercalated lenses of kaolin and thin intercalations of carbonaceous clay. In areas

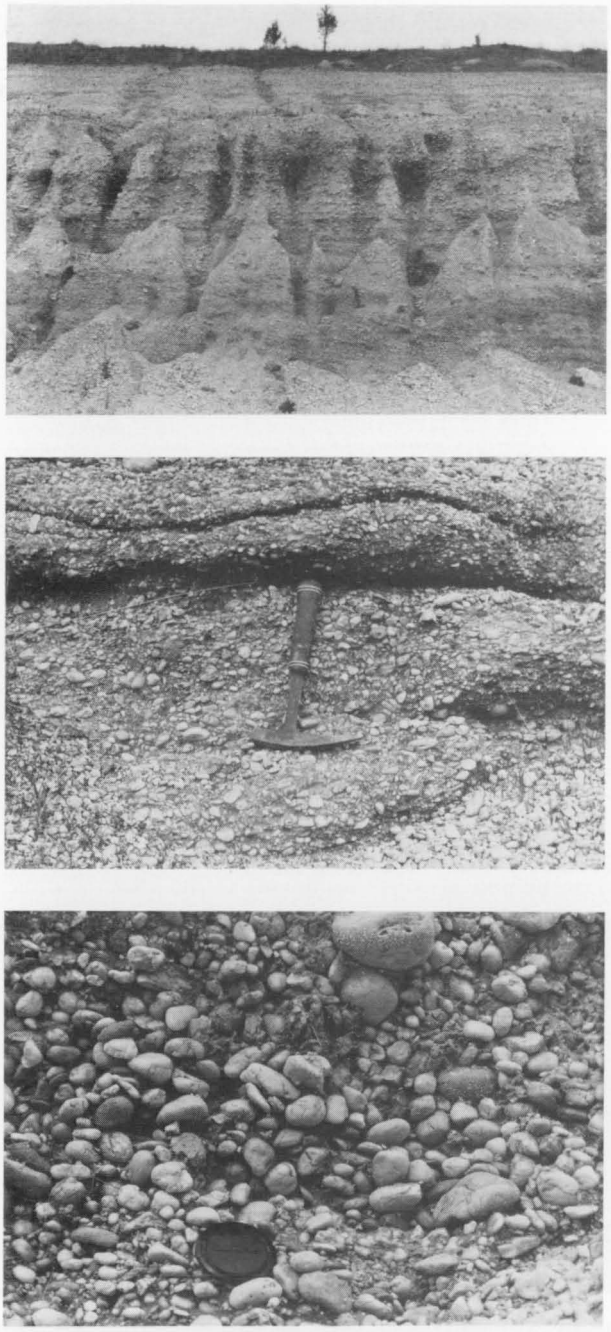


Fig. 104. Tertiary gravels (?Calivil Formation) exposed in aggregate quarry near Urana (northern JERILDERIE); consists of white, rounded, cobble and pebble conglomerate, set in kaolinitic clay matrix.

where the kaolin lenses are well developed, they are differentiated as the Torrumbarry Clay (see Table 29). The sand and gravel are loose to friable in texture, but are weakly cemented by the kaolinitic clay matrix. Grain size diminishes basinward, where the sand is in places grey and pyritic or dark brown and ferruginised, and contain increasing components of interbedded carbonaceous silt and clay.

At the basin margins, poorly sorted clasts range in size from fine-grained to cobble-sized gravel. Granules consist predominantly of pale grey to white, sub-rounded to rounded, low sphericity quartz; larger quartz cobbles are well-rounded and spherical. These are locally associated with free gold and cassiterite, including gold nuggets. Mafic mineral and lithic clasts, other than quartzite clasts, are almost entirely absent. Grains are coated by a kaolinitic clay, which also forms the predominant component of the matrix, and normally has a silty texture due to the presence of fine quartz sand grains. Minor carbonaceous and ligneous sand, silt, and clay, as well as woody debris, occur within the Calivil Formation. These have been particularly noted beneath the Goulburn Valley between Murchison and Seymour, beneath the Murray Valley east of Katunga, and beneath the Ovens Valley (M.A. Reid, Rural Water Commission of Victoria, pers. comm., 1989). Generally, the grain size within the formation becomes increasingly fine in both upward and basinward directions. At the margins of the basin, for example, cobble conglomerate, which predominates at the base of the unit, is replaced up-sequence by sand and sandy clay (Lawrence, 1975). In the Loddon Valley, coarse gravels persist as far north as Bridgewater (ST. ARNAUD), beyond which they are rapidly replaced by coarse sand and gravel (Macumber, 1983). Farther into the basin, the gravel components are absent, the sands become finer, and the silt and clay content of the formation increases substantially. Sand grains include increasing proportions of angular lithic clasts, and sands are generally described as yellow-brown rather than white, although some sands are black. Many grains are coated in a ferruginous cement and pyrite aggregations are common.

Poorly known carbonaceous silt, sand, and clay, which are stratigraphically equivalent to both the Upper Miocene–Pliocene Calivil Formation and Bookpurnong beds, occur beneath the central-western areas of the Riverine Plain, both in northern Victoria (Macumber, 1978a) and in New South Wales [e.g. 'Bookpurnong Beds Equivalents' in Woodside Balranald No.1 (Fig. 52) – Benbow, 1962,

and Ludbrook, 1962a]. They are herein included in the Calivil Formation, but future investigations may allow their differentiation as a separate unit.

Distribution and thickness. Thin sequences of Calivil Formation underlie much of the Riverine Plain, and southeastern and northern fringes of the basin. Thick sequences extend into adjacent highland valleys to the south and east, where the formation forms the youngest of several Tertiary 'deep-lead' systems (Fig. 103). The formation is an important aquifer, and has also been intensively worked for placer gold deposits. Consequently, it has been extensively drilled, and groundwater and mineral exploration bores have been used to define the traces of a number of 'deep leads' (Hunter, 1909) beneath the upper Murray, Kiewa, Mitta Mitta, Ovens, Goulburn, Campaspe, Loddon, Avoca, and lower Wimmera River Valleys. Beneath these valleys the formation is restricted in distribution to infilled entrenchments (Fig. 103) within buried palaeovalleys concealed beneath 40–60 m of Shepparton Formation. The infilled entrenchments are themselves up to 5 km wide and are incised 30–60 m into underlying Tertiary sediments of the Renmark Group, and adjacent Palaeozoic basement (Macumber, 1978a,b, 1983). Within the highland zone to the south, a dendritic pattern of buried former palaeochannels has been mapped on BENDIGO and ST. ARNAUD. These indicate that the Pliocene drainage systems were broadly similar to those of the present-day, although within some of the higher valleys, stranded Tertiary remnants of former channels occur in interfluvial areas, preserved beneath basaltic lava flows. To the north, the 'deep leads' can be traced beneath the Riverine Plain approximately as far as the present-day course of the Murray River, where they emerge from the entrenchments, fan out and coalesce to form an extensive sheet of sand-dominated sediment (Tickell & Humphrys, 1987). The Avoca deep lead was first described by Murray (1896, 1898), and subsequently by Hunter (1909) and in the Mines Department of Victoria Annual Reports for 1915 and 1916. The Powlett Plains deep lead was described by McKenna & Partners (1978), and the Loddon deep lead by Macumber (1978a,b, 1983). Within the basin and beneath the lower courses of the tributary valleys, the Calivil Formation is entirely concealed.

The sands and gravels are thickest in the valley entrenchments and adjacent alluvial fans. Wilkinson (1907) recorded thicknesses of between 90 and 120 m within the 'deep leads' of northern Victoria. Brown & Stephenson (1986) recorded 503 bores which have encountered the entire section of the Calivil Formation, with an average thickness of 62 m. Thicknesses approaching 100 m have been recorded locally, but these possibly include sands from underlying or overlying formations. Some variations in thickness beneath the Riverine Plain partly reflect local deposition of the formation in channels incised into underlying sediment of the Olney Formation, and partly reflect interfingering with the overlying Shepparton Formation. Beneath the eastern margin of the basin, where the Murrumbidgee exits from the confinement of its highland valley, the Calivil Formation forms part of a major concealed alluvial fan ('Murrumbidgee Fan').

Outcrop and geomorphic expression. The formation is mainly concealed but equivalent high-level gravel and sand are exposed in the Victorian Highlands (Kenley, 1976c, 1988c), and similar coarse gravel of possible Calivil Formation are locally exposed in the Urana area of the southeast Riverine Plain in JERILDERIE (Fig. 104). Equivalent sands are also exposed in the elevated Dundas Tableland, in HAMILTON, where some 30 m of ?Calivil Formation and ?Loxton–Parilla Sands equivalents occur (Dorodong Sand of Kenley, 1971).

Internal geometry. Within the Murray Basin, the Calivil Formation forms an extensive, but locally discontinuous sand sheet. Boreholes drilled within the Cainozoic sequence beneath tributary highland valleys have shown that the formation forms narrow confined 'deep leads' which infill previously eroded entrenchments within older units. Sand of the upper part of the formation locally extends beyond the limits of the entrenchments. Macumber (1973) noted upward-fining cycles within the Calivil Formation in northern Victoria.

Palaeontology. The formation contains carbonaceous debris, but is generally poorly fossiliferous in terms of preservation of diagnostic material. Plant remains include sclerophyll leaves, fruit and stems. Diatoms have also been observed within some lenses of fine-grained sediment (Lawrence, 1975). In Woodside Balranald No.1 well (Fig. 52), ?deltaic/?paralic equivalents of the Calivil Formation have earthy coal, coalified plant remains, pyritised molluscan fragments, crustacean fragments and rare foraminifera, including *Ammodiscus* sp. ('Bookpurnong Beds Equivalents' of Ludbrook, 1962a).

Age evidence. Beneath the Riverine Plain, in the Hay–Balranald–Wakool districts the Calivil Formation has been found to contain poorly preserved Pliocene palynological assemblages (Martin, 1977, 1984,a,b,c), which are dominated by *Myrtaceae–Casuarina* pollen (e.g WRC. bore 36102 at 76–78 m;

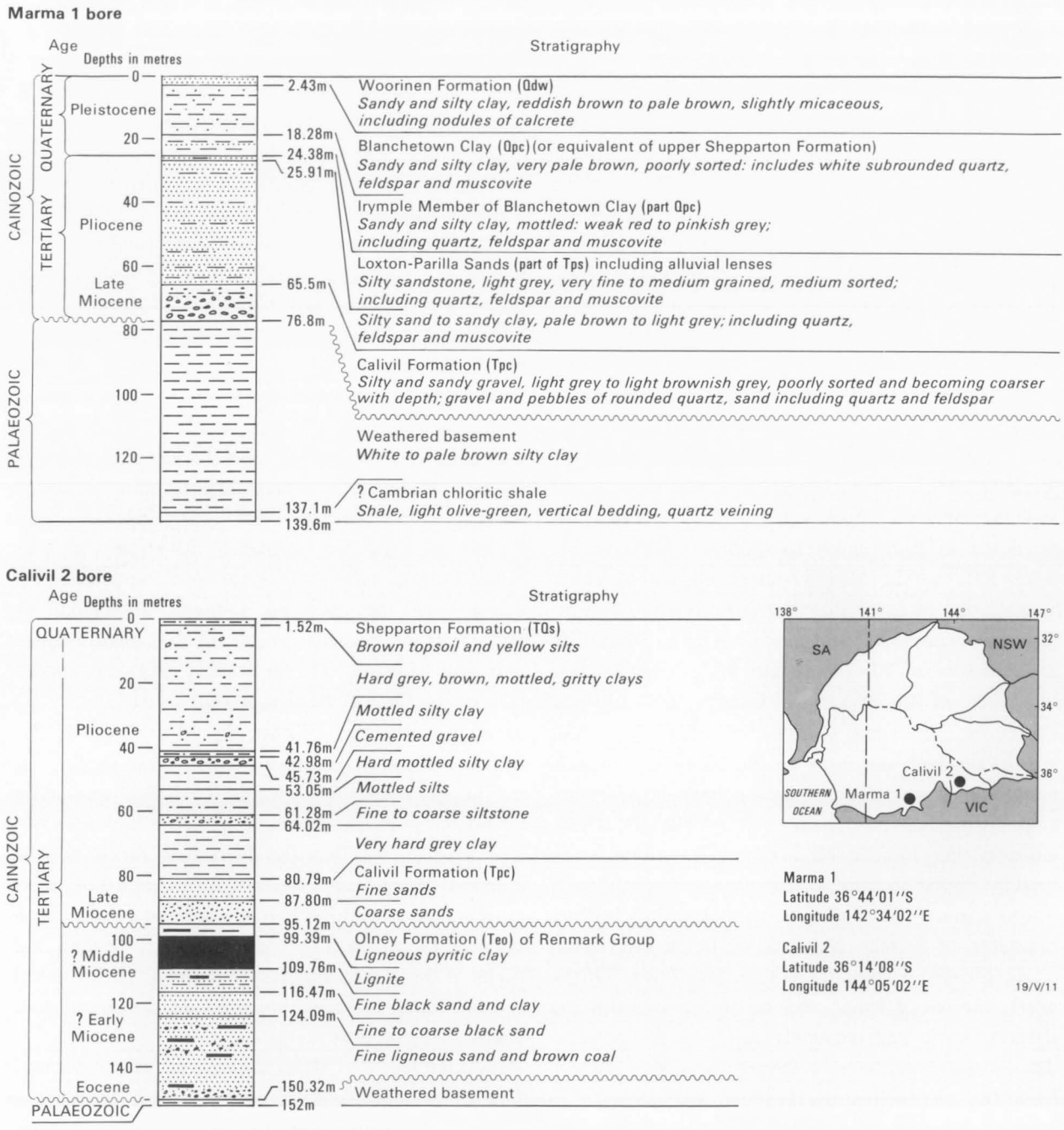


Fig. 105. Type section of Calivil Formation in Calivil No. 2 bore (bore 317-2) on BENDIGO, and representative section in Marma No. 1 bore (bore 1052-1) on ST. ARNAUD (based on Macumber, 1973; Lawrence, 1975).

Martin, 1977). Ludbrook (1962c) determined a ?Late Miocene age for brown, ferruginised, and grey pyritic sandstone ('Bookpurnong Beds Equivalents') in Woodside Bundy No.1 well (Fig. 30). Similarly, in Woodside Balranald No.1 well (Fig. 52) Ludbrook (1962a) dated ?deltaic carbonaceous sand and silt of the Calivil Formation (or its equivalent) as Late Miocene–Pliocene. The formation can also be placed in the age range Late Miocene–Pliocene on stratigraphic grounds. Beneath parts of the Riverine Plain, the formation disconformably overlies sediments of the Olney Formation with *T. bellus* Zone palynological assemblages dated as Middle Miocene in age (Martin, 1977, 1984a,b,c), thereby providing a lower age limit to the formation. The formation is thought to be partly stratigraphically equivalent to the Bookpurnong beds, which have been dated as Late Miocene to Pliocene on foraminiferal and macrofossil evidence. A Late Miocene to Pliocene age has been determined from pollen samples from

TABLE 29. UPPER MIOCENE – PLIOCENE TORRUMBARRY CLAY

Unit: Torrumbarry Clay

Age: Late Miocene to Pliocene

Map symbol: mainly included in Tpc

Synonyms: 'Torrumbarry Clay Member of Shepparton Formation', 'Echuca Formation'

Lithology. Lensoid deposits of white to pale-grey kaolinitic clay, silty clay, and sandy clay; intercalated mainly above, but also within, sand and granular conglomerate deposits of Calivil Formation.

Distribution, thickness and outcrop. Intercalations of kaolinitic clay occur throughout Calivil Formation, beneath southeast Murray Basin; up to 30 m recorded (Lawrence & Abele, 1976, 1988). Almost entirely concealed, but exposed in surface kaolin mines in Oaklands – Coorabin area (JERILDERIE). Isolated outcrops occur within highland fringes of Murray Basin.

Age evidence. Not directly dated, but intercalated mainly within Calivil Formation, and hence of probable Late Miocene – Early Pliocene age.

Environment of deposition. Formed from clay transported from eroded kaolinised Palaeozoic basement rocks in adjacent highland areas (Lawrence, 1975). Weathering thought to have taken place mainly during period of formation of 'Mologa Surface' in Late Miocene – extended period of weathering also thought to have resulted in almost total dominance of residual quartz clasts and absence of lithic clasts. Lithic clasts increasingly common basinwards. Some equivalent kaolinitic clays in adjacent highlands deposited in lakes dammed by basalt flows of late Miocene to Pliocene age (Wellman, 1974).

Stratigraphic nomenclature and type section. Named by Lawrence (1975) after township of Torrumbarry, 24 km NW of Echuca (BENDIGO). Interval 58 – 77 m, in Vic.D.M. Echuca North No.1, nominated as type section (Fig. 106) – 20 m of massive white kaolinitic clay, overlying sands of Calivil Formation and underlying mottled clays of Shepparton Formation. Lawrence (1975) also reported presence of 'Torrumbarry Clay' between 108.3 – 135.1 m.

Stratigraphic relationships and remarks. Type section conformable over sands of Calivil Formation, and conformable under mottled clays of Shepparton Formation. Lawrence & Abele (1976, 1988), however, expanded concept of unit to include similar clay sediments intercalated both within and beneath Calivil Formation. Tickell (1977a) further modified concept by suggesting type section in Vic.D.M. Echuca North No.1 (Fig. 106) disconformable over Calivil Formation, and therefore renamed unit 'Torrumbarry Clay Member of Shepparton Formation' – he re-assigned 'Torrumbarry Clay' of Lawrence & Abele (1976, 1988) to 'Echuca Formation', and nominated interval 108.3 – 135.1 m in Vic.D.M. Echuca North No.1 as new type section. However, although kaolinitic clays are typical of Calivil Formation, and most occurrences can be assigned to that formation, similar clays also occur within overlying and underlying formations at basin margins – in this Bulletin we suggest that name 'Torrumbarry Clay' be retained to describe all undifferentiated white kaolinitic clays, and that new names be adopted when sufficient data become available to allow definition of components of various ages.

Economic geology. In Oaklands – Coorabin region Torrumbarry Clay mined by open-cut and underground methods, for use in manufacture of refractories. Seams of good quality clay are 1.5 – 2.5 m thick and occur at depths of 9 – 18 m (Bembrick, 1974). Equivalent sedimentary clay deposits of probable Late Miocene – Pliocene age mined at Axedale, Enfield, and Ballarat in adjacent northern Victorian Highlands – used in manufacture of pipes, tiles, pottery and in paper industry.

Data sources. Lawrence (1975), Lawrence & Abele (1976, 1988), Tickell (1977a), Tickell & Humphrys (1979).

beneath the Goulburn and Ovens Valleys (Archer, 1983; Tickell & Humphrys, 1987). In addition, within many of the highland valleys of northern Victoria the Calivil Formation is overlain by valley-fill basalt, which has been variously dated as Late Miocene to Pliocene in age, providing local upper age limits on parts of the formation.

Characteristics. At the basin margins, the principal characteristic of the Calivil Formation is the presence of poorly sorted quartz cobbles, pebbles and coarse sand grains in a white kaolinitic matrix. The underlying sand of the Olney Formation generally has abundant carbonaceous material, whereas the overlying Shepparton Formation consists of mottled clay and multi-coloured sand, which are generally polymictic in comparison with those of the Calivil Formation. These distinctive lithologies are well developed beneath eastern and northern areas of the Riverine Plain (Lawrence, 1975; Woolley & Williams, 1978). However, in some boreholes in tributary valleys within the northern Victorian Highlands, the Renmark Group, Calivil Formation and Shepparton Formation each include coarse-grained sand and conglomerate with a kaolinitic matrix (Tickell & Humphrys, 1979, 1980). Consequently, in the absence of palynological control, formation boundaries can be difficult to identify in some of these boreholes. Similarly, in many boreholes beneath the western Riverine Plain, the Calivil Formation consists predominantly of clay and includes abundant carbonaceous interbeds, and therefore does not always provide a sufficiently distinctive marker unit between the Olney Formation and the Shepparton Formation (some Calivil equivalents may have been placed in the Shepparton Formation in this area).

Interpretation of environment of deposition. The coarse components of the Calivil Formation at the basin margins are thought to have been deposited in fluvial valley-fill and alluvial fan environments. Beneath the valleys of northern Victoria, Macumber (1973) interpreted the valley-fill sand and gravel as downstream extensions of the 'deep lead' systems of the adjacent highland region to the south. Towards the basin margins, the relatively higher coarse sand content of the formation (in comparison with the underlying Olney Formation and overlying Shepparton Formation), and lateral continuity of the sands, suggests deposition in braided channel environments. Sand predominates in the buried Upper Miocene – Pliocene distributary fan which underlies the modern Murrumbidgee, where it exits from the highlands. In contrast, west of Hillston beneath the modern Lachlan River, finer-grained components predominate and sands are confined to distinct chan-

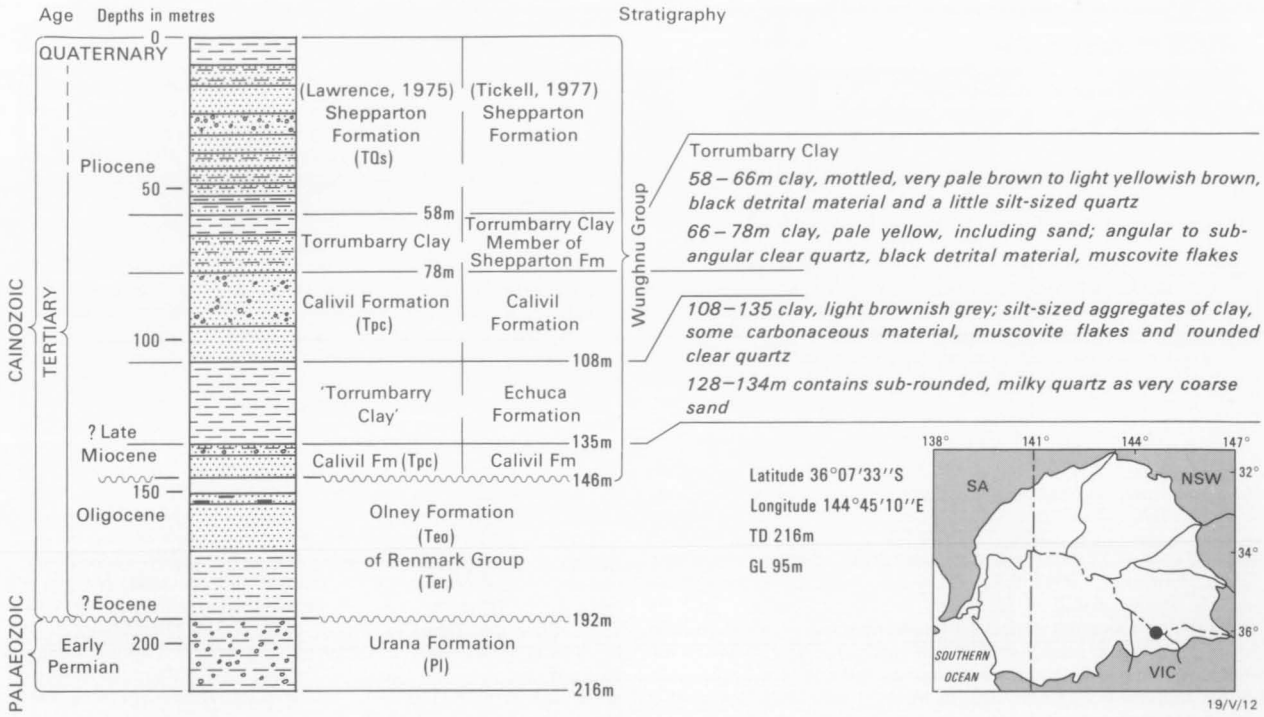


Fig. 106. Lithology log of Vic. D.M. Echuca North No.1, containing type section of Torrumbarry Clay (after Lawrence, 1975); Tickell (1977a) suggested local modification, and renamed upper part of unit "Torrumbarry Clay Member of Shepparton Formation" and lower part "Echuca Formation" – see accompanying text and Table 29 for discussion.

nels, suggesting deposition in a distributary floodplain environment. Similarly, within the sequences deposited farther into the basin, channel sands are increasingly intercalated with silts and clays, and a continuous sand sheet is less clearly defined, suggesting deposition in fluvio-lacustrine and floodplain environments. The carbonaceous content of the relatively fine-grained sediments beneath west-central areas of the Riverine Plain, in combination with the rare presence of marine foraminifera and crustacean fragments (Ludbrook, 1962a,c), is suggestive of deposition in deltaic or paralic environments. Macumber (1978b) identified similar material in boreholes in adjacent areas of northern Victoria, and proposed that they may have been deposited in a transitional environment between the fluvial Calivil Formation and adjacent marine sediments of the Bookpurnong beds and marginal-marine Loxton–Parilla Sands. Evidence of tributary deltas occurs in the lower Loddon Valley (Macumber, 1978a,b). Upper Miocene–Pliocene sediments, which probably include deltaic components, are thought to underlie the central western Riverine Plain, and probably also underlie part of the Darling drainage in the west (see palaeogeographic reconstructions on Fig. 168).

Deposition of the Calivil Formation is thought to have been initiated by a Late Miocene marine transgression associated with deposition of the marine Bookpurnong beds farther west, following a period of weathering and non-deposition or non-preservation, accompanied by erosion in highland valleys. Rising base-levels, accompanying a rise in sea-level, are thought to have resulted in fluvial aggradation by initial back-filling of previously excavated entrenchments in the highland valleys of northern Victoria. As the marine transgression proceeded, the basinward components of the formation (?deltaic/?paralic) were buried beneath transgressive marginal-marine sediments of the Loxton–Parilla Sands. The predominance of quartz pebbles and sand grains reflects the chemical maturity of the Calivil Formation, and the abundant occurrence of associated kaolin probably reflects erosion of the highlands after a period of deep weathering and erosion of basement rocks (Mologa Surface of Macumber, 1978a). The presence of gold placer deposits within the formation also suggests that, during the preceding Late Miocene period, large volumes of basement rock were weathered, eroded

and reworked, concentrating residual gold.

Stratigraphic nomenclature. The Calivil Formation was named by Macumber (1973) after the Parish of Calivil 55 km north-northwest of Bendigo (BENDIGO).

Synonyms. The Calivil Formation was originally named by Macumber (1973), but the name was subsequently modified to 'Calivil Sand' by Lawrence (1975) to reflect the dominant lithology of the formation beneath the southern Riverine Plain in northern Victoria. The name Calivil Sand was subsequently adopted by Woolley & Williams (1978) and applied to similar sediments of equivalent age beneath the Riverine Plain in New South Wales. However, Macumber (1978a,b) and Tickell & Humphrys (1979, 1980) retained the name Calivil Formation. With increasing distance from the basin margins, the formation is lithologically more diverse and includes a higher clay content. In addition, beneath tributary highland valleys the unit includes conglomerate and gravels, rather than just sand. In this Bulletin, we have therefore retained the name 'Calivil Formation' as described by Macumber (1973) in preference to 'Calivil Sand'. The carbonaceous sands and silts, which were referred to as 'Bookpurnong Beds Equivalents' in Woodside Balranald No.1 and Bundy No.1 wells (Ludbrook, 1962a,c), are time-equivalent to the Bookpurnong beds but are thought to be predominantly deltaic in origin, and in this Bulletin have been mainly included with the Calivil Formation, where they are lithologically distinct from the Shepparton Formation. Future investigations may allow them to be differentiated as a separate formation.

Type section. Macumber (1973) nominated the interval between 81 m and 95 m in the Vic. D.M. Calivil No.2 bore (bore 317-2), located 8 km north of Calivil (BENDIGO), as the type section (Fig. 105).

Stratigraphic relationships. Beneath the eastern and northern margins of the Murray Basin, and beneath the tributary highland valleys, the Calivil Formation unconformably onlaps, and is locally entrenched within Palaeozoic basement rocks. Locally, and particularly beneath tributary highland valleys, such as the Loddon Valley (Macumber, 1978b), the formation is unconformably entrenched within eroded sediments of the Renmark Group. The weathered and eroded surface between the base of the Calivil Formation and the underlying Palaeozoic basement and Eocene–Miocene Renmark Group was named the 'Mologa Surface' by Macumber (1978a). Beneath the southeastern margins of the basin, in areas where the Renmark Group is absent, the formation disconformably overlies Lower Permian sediments of the Oaklands Basin. Similarly, beneath northwestern areas of the basin the formation locally disconformably overlies Lower Permian and Lower Cretaceous sediments. Throughout most of its area of distribution, however, the formation disconformably overlies Lower or Middle Miocene carbonaceous sediments of the Olney Formation. In a few bores beneath west-central areas of the Riverine Plain, the formation disconformably overlies black clays of the Geera Clay. Similarly, beneath southwest Victoria the Calivil Formation disconformably overlies calcareous clays of the Winnambool Formation in a very few boreholes.

To the west, the Calivil Formation is stratigraphically equivalent to the marine sediments of the Bookpurnong beds, but the formations have not generally been shown to be in lateral continuity, and are normally separated by marginal-marine sediments of the Loxton–Parilla Sands (e.g. cross-section on SWAN HILL geological map). The Calivil Formation thins into the basin and is also partly replaced laterally by basal components of the Shepparton Formation (e.g. fig. 2 of Macumber, 1978b). It was previously thought that the Calivil Formation may overlie the Bookpurnong beds (as shown in cross-sections by Woolley & Williams, 1978; Woolley, 1978), but revision of the critical borehole logs suggests that the Calivil Formation is absent from boreholes 4486, 5300 (BALRANALD) and 22133 (POONCARIE; Brown, 1983; Brown & Stephenson, 1986). In Woodside Balranald No.1 well, furthermore, carbonaceous silt and sand, previously recorded as a biostratigraphic equivalent of the Bookpurnong beds by Ludbrook (1962a), are probably deltaic or paralic equivalents of the Calivil Formation, similar to material from adjacent areas of northern Victoria identified by Macumber (1978a). Hence, the stratigraphic relationships between the Calivil Formation and the Bookpurnong beds, as seen in boreholes from the New South Wales sector of the basin, appear to be similar to those observed in the Victorian part of the basin.

At the western limits of its area of distribution, the Calivil Formation interfingers with, and is progressively onlapped by, basal components of the Loxton–Parilla Sands (e.g. Kerang Sand Member beneath the lower Loddon Valley; Macumber, 1978a,b), and in the northwest is partly overlain by undifferentiated components of the Loxton–Parilla Sands. The borelog of Vic. D.M. Marma No.1 (Fig. 105; Lawrence, 1975) is typical. Macumber (1983) recorded the presence of a zone of fer-

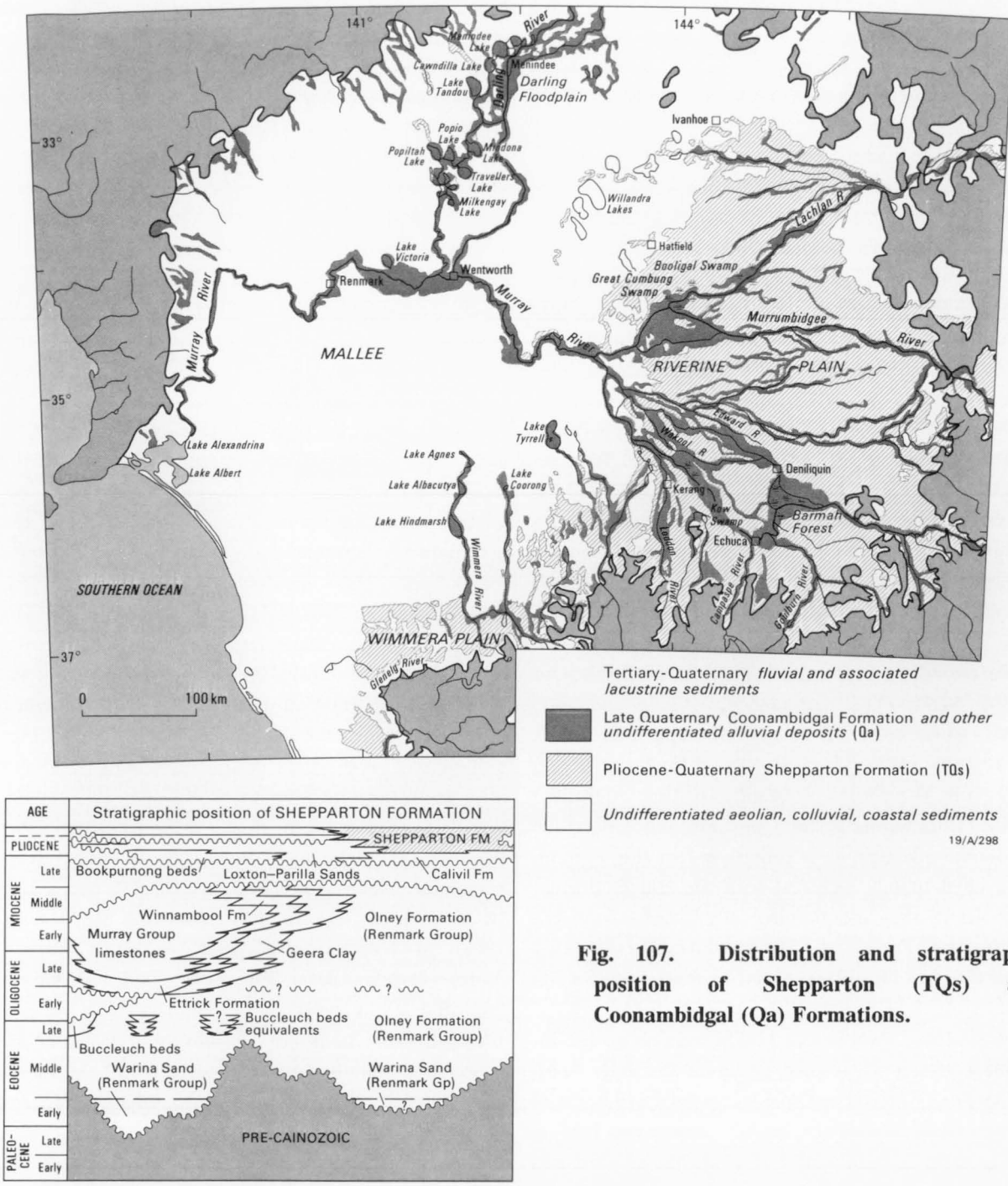


Fig. 107. Distribution and stratigraphic position of Shepparton (TQs) and Coonambidgal (Qa) Formations.

ruginisation separating the Calivil Formation from the overlying Parilla Sand. At the northwestern margin of the basin in South Australia, the Calivil Formation is probably also stratigraphically equivalent to non-marine components of the basal Loxton Sands.

Towards the basin margins, the Calivil Formation characteristically contains kaolinitic clay lenses, and where these are sufficiently well developed they are differentiated as the Upper Miocene–Pliocene Torrumbarry Clay (Table 29). Throughout much of its area of distribution, the Calivil Formation is conformably overlain by, and locally interfingers with, polymictic sand and mottled clay of the Shepparton Formation. The boundary between these two formations can be difficult to identify, and in boreholes beneath the Loddon Valley the Calivil Formation interfingers downbasin with the Yando Clay Member of the Shepparton Formation (Macumber, 1983). Macumber (1983) also recorded, however, that in some bores the contact is coincident with a zone of ferruginisation. Locally, particularly towards the basin margins, where it approaches the surface, the unit is disconformably overlain by coarse sand and

gravel of the Pooraka Formation and other undifferentiated colluvial deposits (Qfr). Within the valleys of northern Victoria, the formation is also locally overlain by alluvium of the Coonambidgal Formation. Within the upper reaches and tributary valleys of many rivers, such as the Goulburn, Campaspe, Loddon and Avoca, probable equivalents of the formation are overlain by basalt flows of the 'Newer Volcanics' (TQv).

Correlative units. The Calivil Formation in the highland valleys of northern Victoria probably correlates with the Lachlan Formation of Williamson (1964, 1969), which occurs beneath the tributary highland valleys flanking the eastern margin of the basin.

Aquifer characteristics. Sands and gravels of the Calivil Formation are highly porous and permeable, and the formation is one of the most important component formations of the basin-wide Pliocene Sands aquifer system, and forms a major pathway for migration of groundwater from the highlands to the Riverine Plain (see 'Groundwater'). At the southern and eastern margins of the basin, the formation currently produces large quantities of good quality water, but farther west and north it generally contains highly saline water. Increasing problems of salinisation have emerged in those areas where potentiometric surfaces approach the groundsurface.

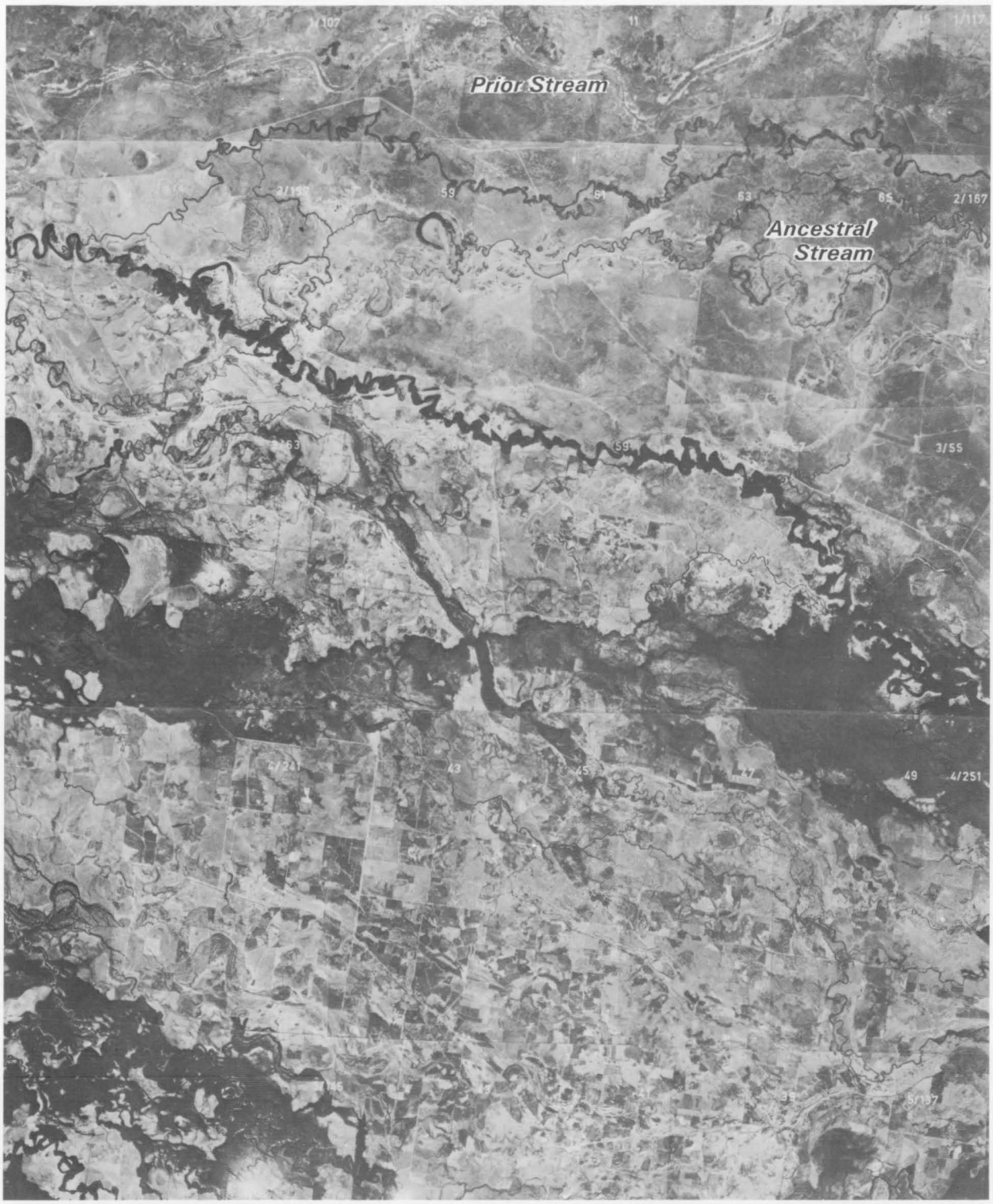
Economic geology. Beneath tributary highland valleys of northern Victoria, coarse sands and gravels of the Calivil Formation form the youngest of the several gold-bearing 'deep lead' systems of northern Victoria (see 'Gold'). Cassiterite has also been identified within some placer deposits. Kaolinitic clay of the associated Torrumbarry Clay is locally mined by open-cut and underground methods (see Table 29).

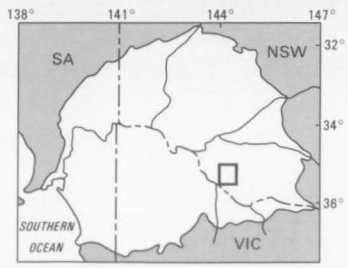
Data sources. Descriptions of the Calivil Formation are presented in Macumber (1969, 1973, 1978a,b, 1983), Lawrence (1975), Lawrence & Abele (1976, 1988), Tickell & Humphrys (1979, 1980, 1987), and Brinkley & others (1988). Description of the placer gold deposits, including detailed maps are recorded in Murray (1898), Gregory (1903), Dunn (1905, 1912a), Wilkinson (1907), Hunter (1909), Hunter & Mulvaney (1937), and McKenna & Partners (1978) – see also references to 'deep lead' sediment, listed under 'Gold'. Equivalent coarse sediments of the Lachlan Formation, beneath the tributary valleys to the east of the basin in New South Wales have been described by Williamson (1964, 1969).

Unit: Shepparton Formation of the Wunghnu Group
Age: Pliocene to Recent in age
Map symbol: TQs
Component members: Lawrence (1966) subdivided the surface and near-surface part of the Shepparton Formation into a number of members based on a modification of soil stratigraphic units recognised by earlier workers mapping soil units: Kialla Member, Katandra Member, Quiamong Member, Widgelli Pedoderm, Mayrung Member (Table 30); Butler (1950) differentiated 'Prior Stream' deposits which Lawrence (1966) placed in the upper Shepparton Formation; Bowler (1978a) distinguished the Green Gully and Tallygaroopna and fluvial complexes; in the subsurface, Macumber (1983) differentiated two sequences within the Shepparton Formation beneath the Loddon Plain of northern Victoria: the upper sequence is unnamed, and the lower sequence was named the Yando Clay Member of the Shepparton Formation.
Equivalent units of western Murray Basin: Upper Pliocene Parilla Sand (S.A.; see Table 26), Upper Pliocene–Lower Pleistocene Moorna Formation (Table 28), Lower Pleistocene Chowilla Sand (Table 31), Pleistocene Rufus Formation (Table 32) – all exposed in cliff sections of the Murray River.

Remarks. On the basis of pedogenic character Butler (1956, 1958) and Butler & Hutton (1956) identified a number of soil stratigraphic units within surface occurrences of the Shepparton Formation. These formed the basis of mappable units on soil maps of parts of the Riverine Plain. Each member was mapped on the basis of geomorphic character (e.g. presence or absence of levee traces), and each is capped by a palaeo-soil, and is disconformably buried by the succeeding member. Lawrence (1975) adopted these units as lithostratigraphic members of the exposed Shepparton Formation (Table 30). However, although these units are mappable in parts of the Riverine Plain they subdivided only the uppermost sequences of the Shepparton Formation. The relative ages of many of the members is known, but absolute dates are lacking. Consequently, subdivisions of the Shepparton Formation based on correlations between widely distributed sections remain uncertain.

Lithology. The Shepparton Formation consists of unconsolidated to poorly consolidated clay, silt and silty clay, with intercalated lenses of fine to coarse sand and gravel. The clay is silty, variegated and mot-





7727 MOULAMEIN 1 : 250 000 Map DENILIQUIN SI 55 – 13

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Fig. 108. Photomosaic of Moulamein 1:100 000 Sheet area, showing 'Prior', 'Ancestral', and modern stream channels; dark areas adjacent to river channels have seasonally flooded forest vegetation.

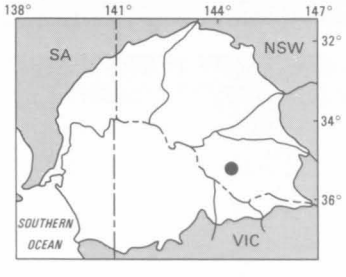
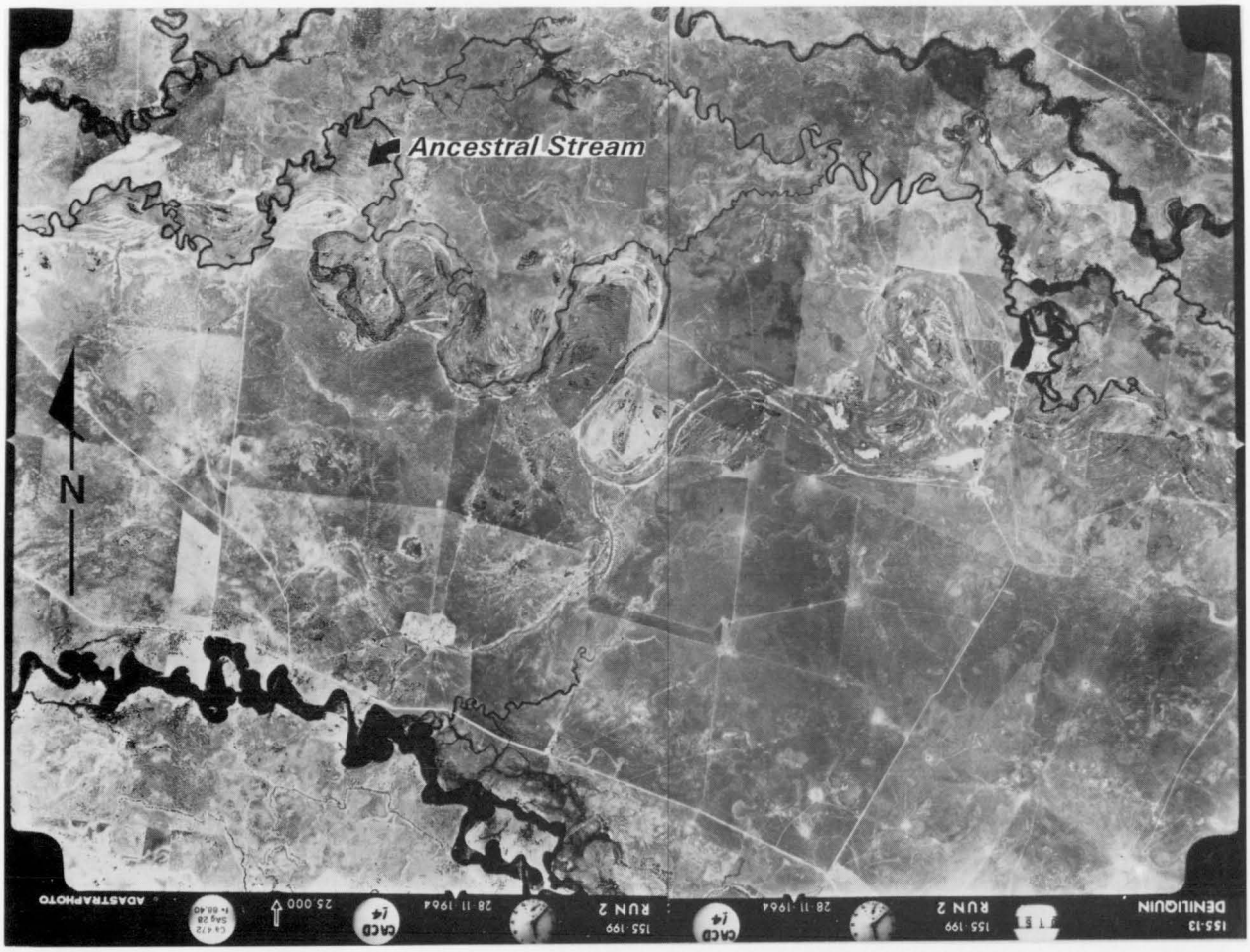


Fig. 109. Airphoto of 'Prior Stream' channel of Riverine Plain (northwest DENILIQUIN); photo from Nationl Mapping RC9 Series, Deniliquin Run 1, No. 110 ; photographed 26/11/1964.

tled, and typically red-brown, yellow, and white. Much of the sequence has been modified by both pedogenesis and fluctuating groundwater tables. The formation also contains numerous red-brown palaeosols and thin humic intercalations. The sand consists of poorly sorted, rounded to angular, high-sphericity to low-sphericity, polymictic grains. Adjacent to areas draining the northern Victorian Highlands, coarse sand and gravel include lithic clasts of the adjacent Palaeozoic basement rocks set in a loosely compacted matrix of poorly sorted sand, silt and clay. Towards the interior of the basin, lithic clasts are less abundant, and the sand increasingly consists of mineral grains of quartz, chert, feldspar, muscovite, with minor biotite, tourmaline, sphene, garnet, epidote, and leucoxene. Lawrence (1975)



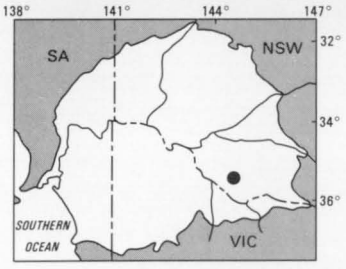


Fig. 110. Airphoto of 'Ancestral Stream' channel of Riverine Plain (northwest DENILIQUIN); photo from National Mapping RC9 Series, Deniliquin Run 2, Nos. 166, 168; photographed 20/11/1964.

noted a median grain size ranging from 0.25 to 7 mm, fair sorting with a coefficient of less than 2, positive skewness in fine-grained deposits and negative skewness in coarser-grained components.

Beneath the alluvial plains of the Powlett Valley and in the Loddon Plain, Macumber (1983) differentiated an upper sequence dominated by brown and grey clay from a lower sequence dominated by red and light grey clay (Yando Clay Member).

Distribution and thickness. The Shepparton Formation underlies the Riverine Plain in the eastern half of the basin, and onlaps hills of folded Palaeozoic rocks of the Lachlan Fold Belt to the north, east and south (Fig. 107). Around the northern margins of the basin, the formation is largely concealed beneath a veneer of aeolian sand ('Qdp'), and is only locally exposed at the surface in areas adjacent to the Darling River. At the western margin of the Riverine Plain, the formation is overlain by, and laterally replaced by, aeolian sands of the Mallee Region. Thick deposits of Shepparton Formation also underlie the tributary valleys of northern Victoria, and extend up to 100 km into the highland zone (e.g. Loddon Valley). In northern Victoria, a narrow zone of Shepparton Formation, locally concealed beneath aeolian sands of the Mallee, extends to the west around the northern fringes of the Victorian Highlands. A thin veneer of Shepparton Formation equivalents (and Coonambidgal Formation equivalents) occurs between stranded ridges of Loxton–Parilla Sands in southwestern Victoria, and similar fluvio-lacustrine (or coastal-lacustrine) sediments extend locally into adjacent areas of southeastern South Australia. The formation has

Fig. 111. Airphoto of fluvial channel morphologies (TQs, Qa) in Goulburn Valley, showing relationships between 'Goulburn River', 'Kotupna Complex' and 'Tallygaroopna Complex' of Bowler (1978a); airphoto from BENDIGO Run 3, No. 62; photographed on 22/11/1963; interpretation shown on insert figure based on part of fig. 3.3 of Bowler (1978a); location of insert figure shown on airphoto.

been mapped on HORSHAM and HAMILTON, but the veneer becomes increasingly thin and discontinuous to the west and the unit has not been identified on adjacent PENOLA and NARACOORTE. On parts of ST. ARNAUD and eastern HORSHAM, the formation forms an extensive but discontinuous blanket over the Loxton–Parilla Sands, broken by minor ridges of the Pliocene sand unit. On western HORSHAM, the Shepparton Formation is confined in distribution to northwesterly trending corridors located between elevated ridges of the Loxton–Parilla Sands.

The thickness of the Shepparton Formation is highly variable reflecting the onlapping nature of the unit. Beneath the eastern and northern margins of the basin it is locally a few tens of metres thick, whereas within some highland valleys and beneath the Riverine Plain thicknesses averaging around 70–80 m are not uncommon. Several bores have encountered over 100 m of section (e.g. parts of DENILIQUIN; Brown & Stephenson, 1986).

Outcrop and geomorphic expression. The Shepparton Formation is the youngest of the major Cainozoic formations beneath the Riverine Plain of the eastern Murray Basin. Vertical profiles, within upper parts of the formation, are locally exposed in recently eroded river cliffs, in entrenched sections of the modern rivers. Younger components of the formation crop out at the surface of the Riverine Plain, where they form extensive flat alluvial floodplains, traversed by remnant traces of inactive, meandering palaeochannels. A description of the surface geomorphology of the Riverine Plain is given in Chapter 3. It is characteristically flat, apart from local sand hills, representing former fluvial sand channels, former levee banks, and fluvial channel-derived aeolian dunes. At ground level, in some areas, such as the Hay Plains, the Riverine Plain appears to be flat and featureless with few trees. Aerial photographs and satellite imagery, however, reveal a wealth of geomorphic detail (Chapter 3). Low-angle distributary fans have been identified on the Lachlan, Murrumbidgee, Goulburn, and Loddon Rivers – with the apex of each fan located where the modern river exits from the highlands. As topographic features, the alluvial fans extend only a short distance from the basin margins, but the distributary channel complexes radiate across the Riverine Plain where they rapidly merge with floodplain deposits. At the eastern margin of the basin in New South Wales, the traces of these distributary fans can be seen on topographic contour maps. Former distributary channels can be identified from the remnant traces of former leveed stream banks.

In the southeastern Riverine Plain, two types of 'end-member' types of abandoned-river-channel have been identified. These consist of recently abandoned channels, which Pels (1964b) referred to as 'Ancestral Streams', and which in many cases preserve sediment included in the Coonambidgal Formation. Elsewhere, remnants of older channels, abandoned at some considerable time in the past, were referred to as 'Prior Streams' by Butler (1950), and these form part of the Shepparton Formation (Figs 108, 109, 110). The prior streams consist of former meander belts, preserved in shallow and discontinuous depressions, and usually identifiable by distinctive channel morphology, vegetation patterns, by the presence of remnant paired sandy levee banks, and minor swamp features. Former channel sands, reworked by aeolian processes, in places form low hillocks ('source-bordering dunes' – see 'Qad'). The former levees are elevated a few metres, whereas the channels form depressions 1–2 m deep and are underlain by channel sand and gravel bodies 6–13 m thick (Skene & Freedman, 1944; Stannard, 1962; Schumm, 1968a,b). In contrast to their modern equivalents, the stream channels carried a coarse sandy bed-load, and as seen on aerial photographs their meanders were of greater wavelength. They were probably created by rivers of greater competence and higher discharge (even if only during seasonal flooding). The prior streams are also associated with extensive aggradational floodplains, unlike the ancestral and modern floodplains, which are entrenched within the older prior stream sediments (Butler & others, 1973). These various types of channel morphology only represent end-members, and there is a spectrum of channel type from the present channels of modern rivers through the ancestral channels to the prior streams. Each end-member is thought, however, to reflect the sensitivity of the fluvial system to past fluctuations in palaeoclimatic and palaeohydrologic conditions (see 'Interpretation of Environment of Deposition').

Following a detailed study of the Goulburn–Murray River confluence area in northern Victoria, Bowler (1966a,b, 1967, 1978a) differentiated the 'Green Gully/Tallygaroopna Complex', and younger 'Kotupna Complex' (equivalent to the Coonambidgal Formation), both of which consist of wide, large wavelength, sand-dominated channels (Fig. 111). In contrast, the younger modern rivers flow in much smaller high-sinuosity channels carrying a suspended load (Goulburn Complex). These complexes possibly correlate with the Coonambidgal I II and III of Pels

(1971), but as noted by Bowler (1978a) the oldest complex (Green Gully/Tallygaroopna) occurs beneath a red-brown soil, and based on the definitions of Butler (1958) and Lawrence (1966, 1975) these are technically equivalent to the Shepparton Formation, although Pels (1971) included similar channels in his Coonambidgal I sub-division of 'ancestral streams'. In reality, a continuum of sub-divisions exists between the Shepparton Formation and the Coonambidgal Formation.

Internal geometry. Where the Shepparton Formation is exposed in present-day river cliffs, it consists of upward-fining, but truncated sets of silt, clay and humic clay, locally cross-cut by poorly sorted upward-fining sand lenses. Borehole sections reveal the shoe-string nature of the laterally discontinuous sand bodies. Lawrence (1966, 1975, 1976a, 1988a) indicated that the channel sands were mainly deposited by lateral accretion, and sand bodies mainly have a flat base due to lateral planation. In addition, sinuous and lobate splay deposits occur adjacent to the levees. Plugs of grey, silty clay infill abandoned meanders, chute channels and cut-off necks. Sand bodies associated with the prior streams (Stannard, 1962; Schumm, 1968a) are lenticular in cross-section, with a relatively narrow base eroded into underlying sediment, and a narrow upper surface. Individual sand bodies are up to 12 m thick, but stable individual channels within the sand body are no more than 3 m thick. The largest sand body examined had a width of 518 m. The sinuosity of nearly all the examined channels was found to be in the range 1.1 to 1.2. (ratio of channel to valley length over a given distance). Channel sands seen in pits (fig. 18B of Schumm, 1968a) and river cliff sections (Tickell, 1977a) are commonly cross-bedded.

Palaeontology and age evidence. Owing to the mottled and weathered condition of much of the Shepparton Formation, few identifiable pollen remains have been described from the formation. Few direct palynological or isotopic ages have therefore been obtained from the Shepparton Formation, and consequently the age of the formation has largely been determined from its stratigraphic position relative to other units. In the Loddon Valley, within the northern Victorian Highlands, sediments of the Shepparton Formation overlie a basaltic flow which has been dated as Late Pliocene (Aziz-Ur-Rahman & McDougal, 1972), thereby providing a lower age limit in that area. In most areas, basal components of the formation overlie or interfinger with sediments of the Late Miocene to Early Pliocene Calivil Formation with apparent conformity. In the past, the Shepparton Formation has been presumed to be mainly of Quaternary age, but geologic cross-sections indicate that the formation is partly equivalent to thick sequences of Pliocene Loxton–Parilla Sands, as well as the Plio-Pleistocene Blanchetown Clay. A large proportion of the Shepparton Formation is therefore likely to be of Pliocene age. Upper components of the formation form the present-day surface of much of the Riverine Plain, and many geomorphic features are well-preserved and likely to be Quaternary, mainly Pleistocene, in age. Recent aeolian loess deposits, palaeosols and lacustrine, fluvial and colluvial deposits have locally been included in the Shepparton Formation. The aeolian landforms of the western Murray Basin are thought to have developed predominantly over the past 400 000–700 000 yrs and, therefore, those surface components of the Shepparton Formation which contain an aeolian parna component (see 'Woorinen Formation') are likely to be no older than Late Pleistocene.

Radiocarbon dates obtained from exposures of upper components of the formation indicate a predominant Late Pleistocene, rather than Holocene age (Langford-Smith, 1963; Pels, 1964a,b, 1969a,b; Gill & Bethune, 1976; Bowler, 1967; Bowler & Polach, 1971). Pels (1964b) found that radiocarbon dates from prior streams near Griffith indicated that sedimentation commenced before 36 000 yrs.BP, the limits of the method. The last major transition from large sandy channels to small suspended load channels of the modern rivers was subsequently placed between 11 000 and 14 000 yrs.BP (Bowler, 1978a; Bowler & Wasson, 1984).

Characteristics. The clay and sand of the Shepparton Formation are mottled and multi-coloured, whereas the underlying Calivil Formation is characterised by the presence of quartz sand with a white kaolinitic matrix. Sediment of the Shepparton Formation is distinguished from that of the overlying Coonambidgal Formation by geomorphic expression and the lack of weathering in the younger unit. In some boreholes beneath areas of the western Riverine Plain, the Calivil Formation consists predominantly of clay and does not provide a distinctive marker between the Olney Formation and the Shepparton Formation. In these boreholes, palynology may be required to establish the boundaries between the Tertiary units. Older equivalents of some of the present-day morphostratigraphic units mapped on the Riverine Plain, such as 'source-bordering dunes' of Qad and lacustrine sediments of Ql, have not been differentiated in the subsurface, and

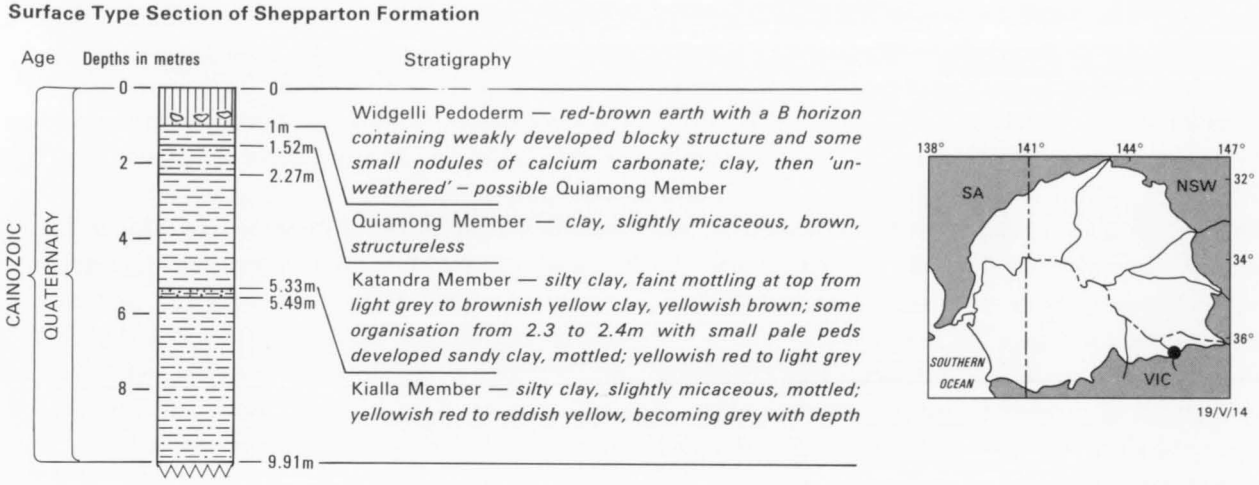


Fig. 112. Surface type section of Shepparton Formation exposed in concave bank of Goulburn River, at Kialla (BENDIGO), 6.4 km south of Shepparton (after Lawrence, 1966, 1975).

are therefore included in the Shepparton Formation. At the basin margins, sand and gravel of the Shepparton Formation have been differentiated from those of the Pooraka and other colluvial footslope deposits by the presence of chaotic boulder/cobble beds in the latter.

Interpretation of environment of deposition. The occurrence of poorly sorted, upward-fining, truncated sets of sand, silt and clay, capped by humic clays and palaeosols, in combination with a lack of marine fossils, indicates that the Shepparton Formation was deposited in an extensive fluvio-lacustrine environment. Much of the formation consists of mottled clay and silt, which appear to have been deposited mainly in overbank and lacustrine environments within an aggrading floodplain. The floodplain deposits are locally traversed and incised by channel sand and gravel with associated sand and silt levee and splay deposits.

Many of the depositional processes indicated above clearly still operate within the entrenched river courses of the modern Riverine Plain (see 'Coonambidgal Formation'). In addition, the Shepparton Formation exhibits a complex array of palaeodrainage features (prior streams) some of which, as noted above, are different from those of the modern rivers, and appear to have developed in response to a different hydrologic regime from that which operates at the present-day (Figs 108, 109, 110, 111). These differences have been interpreted in terms of palaeoclimatic influence, and reflect the sensitivity of the fluvial landscape to changes in rainfall, and consequent changes in vegetation cover, runoff, stream discharge, sediment load and type. The large wavelength-type meander belts, with their associated sandy bed-load deposits of the prior stream systems, were interpreted to reflect periods of greater discharge in the past. However, various authors have arrived at different conclusions as to whether these features formed during periods of greater discharge due to a pluvial phase, or as is currently thought during arid-phase floods when sediment was readily available. Similarly, some authors initially suggested correlation with interglacial periods (e.g. Cotton, 1963), while others suggested correlations with glacial aridity (e.g. Bowler, 1978a).

Butler (1950) thought that deposition of the sand-dominated channels of the prior streams occurred during a period of greater aridity than at present, when streams were unable to cross the Riverine Plain. He based this conclusion partly on the fact that soils bordering the prior streams are relatively saline, and are associated with the aeolian clay aggregates of the Widgelli Pedoderm. Hawkins & Walker (1956) suggested the prior stream channels were cut during a period of increased runoff due to a wetter climate, but attributed sand deposition to diminished runoff during periods when the climate became more arid. Langford-Smith (1959, 1960a,b, 1962) considered that the large channel size of the prior streams indicated that they carried increased discharge compared with the modern rivers and advocated a humid climate. Stannard (1962) suggested that the channels may have been incised during a period of increased runoff, but were back-filled during a period of aridity when the ratio of sediment to runoff increased.

Near Darlington Point, Schumm (1968a) examined small, intermediate and large channels of the

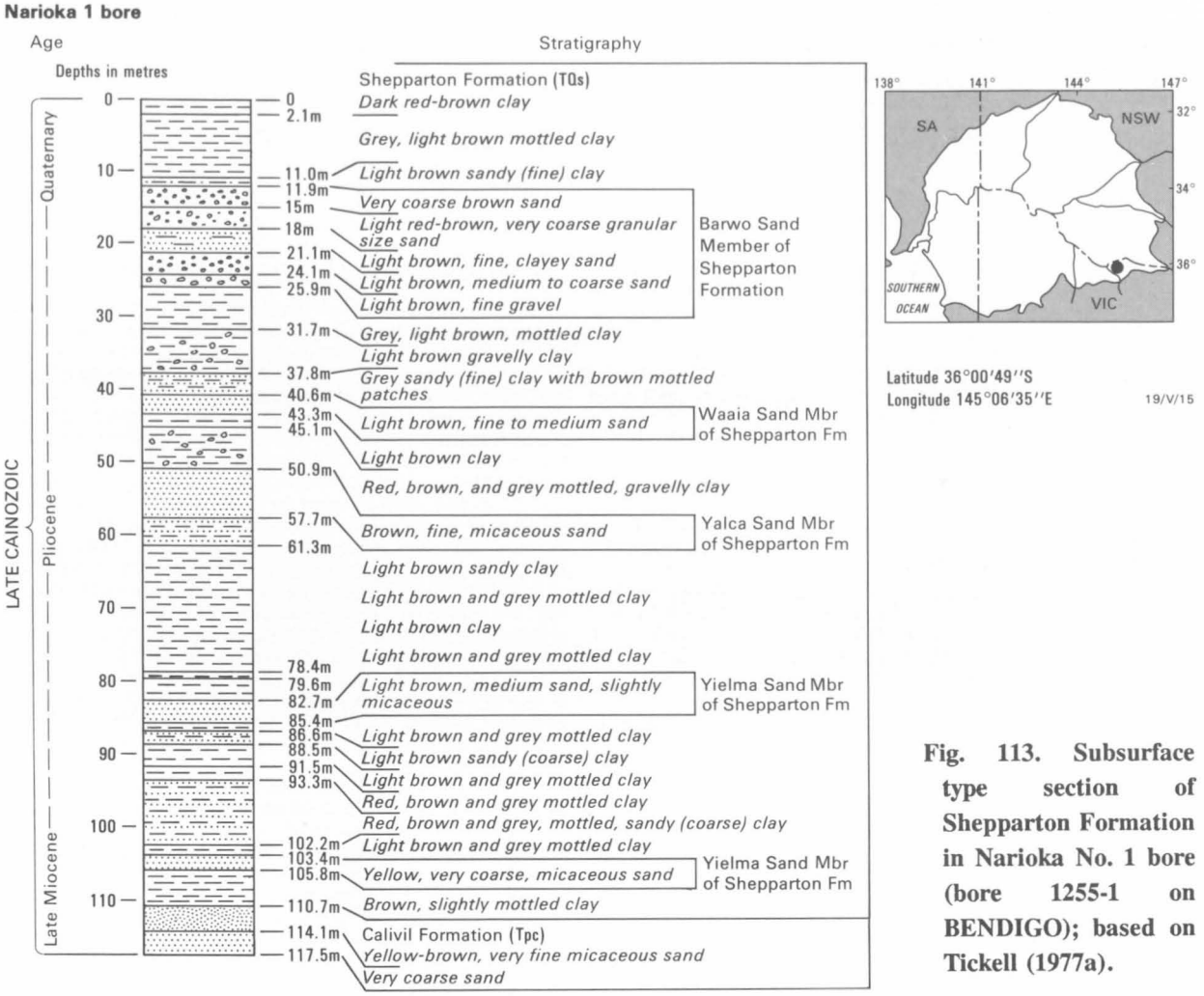


Fig. 113. Subsurface type section of Shepparton Formation in Narioka No. 1 bore (bore 1255-1 on BENDIGO); based on Tickell (1977a).

prior stream system, and calculated that the bank-full discharge of the smallest channel (meander wavelength 5.5 km) would have been 651 m^3/s, transporting a daily total of 54 000 tons of sand at a bankfull water velocity of 1.6 m/s. The intermediate-sized channel had a bankfull discharge of 2068 m^3/s. carrying a daily total of 140 000 tons of sediment at a bankfull water velocity of 1.9 m/s, and the large channel is interpreted to have had a bankfull discharge of 8212 m^3/s, transporting a daily total of 510 000 tons of sand at a bankfull velocity of 2.7 m/s. These figures are greatly in excess of equivalent figures calculated for the modern river channels (see description of Coonambidgal Formation), but could reflect high peak flooding due to a lack of vegetation cover, rather than high annual run-off. Schumm concluded that the straight, high width-depth ratio, bed-load prior stream channels should be related to a drier climate than that of the present. He suggested that a change to a drier climate would have resulted in removal of the cover of protective vegetation in the adjacent eastern highlands, followed by increased erosion and sediment input to the basin, and that the bed-load sands were deposited during periods of high flood peaks during this arid phase of generally low highland run-off but high sediment input. He was unable to determine whether the arid phase correlated with glacial or interglacial periods.

Bowler (1978a) also correlated the high discharge sand-dominated channels with an increased sediment input associated with reduced vegetation cover and high seasonal run-off, but suggested that this accompanied glacial and periglacial activity in the southeastern highlands, when vegetation cover was minimal, and sediment input and run-off high during periods of spring/summer melting. The concept of deposition of the prior streams during arid phases is supported by the local occurrence of large aeolian 'source-bordering' dunes. These are located mainly on northern or northeastern margins of the larger channel complexes, and their sands represent the down-wind products of deflation of exposed point-bars and other fluvial channel sands (see description of Qad).

Surface components of the upper Shepparton Formation include intercalated aeolian sandy and

TABLE 30. QUATERNARY SURFACE MEMBERS OF THE SHEPPARTON FORMATION, SOUTHERN RIVERINE PLAIN

Unit: Kialla Member of Shepparton Formation

Age: Pleistocene

Map symbol: included in TQs

Lithology. At Kialla type locality (Fig. 112) weathered sandy clay, but elsewhere ranges from clay to gravel. Weathered upper portion mottled pale-reddish-brown to light olive-grey silty clay. Changes with depth to pale-yellowish-grey silty sand. Internal stratification generally absent.
Distribution and thickness. Not recognised at surface of Riverine Plain, but Lawrence (1976a, 1988a) noted locally exposed at number of stream-bank localities; described only at type locality where 4.5 m thick.
Environment of deposition. Part of fluvio-lacustrine Shepparton Formation. Mixture of channel sands and finer-grained floodplain deposits.
Stratigraphic nomenclature and type section. Named after Parish of Kialla, 6.5 km south of Shepparton (BENDIGO). Type locality in Goulburn River section at Kialla (Fig. 112).
Stratigraphic relationships. Occurs in uppermost Shepparton Formation and is basal unit of surface and near-surface units recognised by Lawrence (1966, 1975, 1976a, 1988a). At type locality, Kialla Member disconformable under Katandra Member, and underlain by older undifferentiated components of Shepparton Formation.

Unit: Katandra Member of Shepparton Formation

Age: Late Pleistocene

Map symbol: included in TQs

Synonym: Katandra depositional system

Lithology. Deeply weathered clay, silty clay, sandy clay, minor intercalated sand lenses; buried soils at top may be red-brown, brown or grey, and may be calcareous or non-calcareous. Typically thick, well-differentiated weathering profiles with leaching of carbonate, segregation and weathering of mineral grains. Soil developed on Katandra mature and highly differentiated (Butler, 1958).
Distribution and thickness. Thought to occur at shallow depths (few cm to few m) beneath large tracts of Riverine Plain, but exposed at surface only in eroded river bank sections.
Environment of deposition. Sand stringers deposited in fluvio-lacustrine environments, similar to those of present-day leveed river systems (Butler, 1958; Lawrence, 1975, 1976a, 1988a). Butler (1958) suggested may include significant aeolian component in form of parna; suggested not simple sheet-like deposit, but a generic group of undifferentiated layers of riverine and aeolian origin subject to widespread weathering prior to burial beneath succeeding Quiamong and Mayrung Members. As originally envisaged by Butler (1958), upper surface of Katandra represents major buried landscape or surface of non-deposition. Lawrence (1975, 1976a, 1988a) expanded definition to include all sediments which immediately underlie buried surface.
Stratigraphic nomenclature, synonyms, and type section. Named after Parish of Katandra, 20 km northeast of Shepparton (WANGARATTA). Katandra Member of Lawrence (1966) modified from 'Katandra' depositional system of Butler (1958). 'Katandra' also correlated with 'Bingar' parna unit of Van Dijk (1958). Butler (1958) described typical profile through 'Katandra' on banks of Narrancoolambund Lagoon, Parish of Colaragang, N.S.W. (Fig. 115) – profile of 15 cm of grey fine sandy clay with weak angular blocky structure and fine rusty and black flecks and concretions (clays super plastic when moist). Grade down profile into 60 cm of grey and dark-grey mottled clay with moderate angular blocky structure, further underlain by 1.2 m yellow-grey, yellow-brown coarsely-mottled, micaceous, crumbly, fine sandy clay. Lawrence (1975) subsequently described Katandra Member in his type section of Shepparton Formation at Kialla (Fig. 112).
Stratigraphic relationships. Katandra Member first highly weathered surface encountered below Widgelli Pedoderm. Numerous other, similarly weathered profiles known to occur below Katandra Member, but only Kialla Member described and named. Presence of deeply weathered upper profile suggests major period of non-deposition prior to deposition of overlying Quiamong Member (Butler, 1958).

Unit: Quiamong Member of Shepparton Formation

Age: Late Pleistocene

Map symbol: included in TQs

Synonym: Quiamong depositional system

Lithology. Clay, silty clay, and micaceous sandy clay, characteristically unweathered. Buried components show little evidence of major soil development. Red-brown earths, grey and brown non-calcareous soils overlie surface occurrences; locally these have gypsum horizons and minor calcium carbonate concretions.
Distribution and thickness. Widely distributed throughout Riverine Plain. Towards margins underlies separate ribbon-like tracts which coalesce 50–100 km into basin to form laterally continuous sheet. Most surface exposures of Shepparton Formation in Victorian sector of Riverine Plain assigned to Quiamong Member (Lawrence, 1975). Former channels incised some 6 m into older sediments, and sediments flanking former channel deposits up to 3 m thick.
Outcrop and geomorphic expression. Over much of Riverine Plain concealed beneath Widgelli Pedoderm and Mayrung Member, but in places remnants of former channel deposits (prior streams) slightly elevated few metres relative to adjacent areas. Channel traces and residual segments of former levees locally preserved.
Environment of deposition. Deposited in fluvio-lacustrine environments by leveed stream systems (Lawrence, 1975). Butler (1958) suggested absence of soil development indicates time interval between deposition of Quiamong and overlying Widgelli Pedoderm relatively short.
Stratigraphic nomenclature, synonyms and type section. Named after Parish of Quiamong, 29 km northeast of Deniliquin (DENILIQUIN). Quiamong Member of Lawrence (1966, 1975) modified from 'Quiamong' of Butler (1958). Original type section of 'Quiamong system', as nominated by Butler (1958), located on eroded margins of Narrancoolambund Lagoon, Lot 63, Parish of Colaragang, County Cooper, 2 km east of Darlington Point (Fig. 115). Number of additional profiles in type area described by Butler (1958). Lawrence (1975) identified Quiamong Member in his description of type locality of Shepparton Formation (Fig. 112).
Stratigraphic relationships. Over much of Riverine Plain forms unweathered interval between Widgelli Pedoderm and underlying deeply weathered sediments of Katandra Member. Locally, unconformably incised within Katandra Member and older components of Shepparton Formation. In parts of Riverine Plain, overlying members absent and unit exposed at surface. Disconformable under Mayrung Member.

Unit: Widgelli Pedoderm of Shepparton Formation

Age: Late Pleistocene

Map symbol: included in TQs

Synonyms: 'Widgelli Parna', 'Widgelli Member'

Lithology. Essentially soil stratigraphic unit which forms prominent marker horizon within upper levels of Shepparton Formation of Riverine Plain. Primarily reddish-brown calcareous clay. Where buried beneath overlying Mayrung Member, relatively unleached and unmodified. Surface occurrences characterised by well-differentiated soil, with dense to loose 'A' horizon lacking calcium carbonate, and 'B' horizon with relatively abundant calcium carbonate.
Distribution and thickness. Forms extensive sheet which overlies large tracts of Riverine Plain; generally 1–3 m thick.
Environment of deposition. Thought to have been deposited as aeolian dust (parna), which Butler (1956) and Butler & Hutton (1956) suggested derived from aeolian dunefields of Mallee region to west. Crocker (1946) previously suggested calcareous component derived from carbonate sediments of coastal areas exposed during Quaternary periods of lowered sea-level. In contrast, Pels (1964a) and Blackburn (1966a) suggested aeolian materials derived largely from adjacent deflation centres within Riverine Plain. Sleeman (1966) noted parna deposits at Darlington Point have angular grains and, in addition to quartz grains, also contain chemically immature minerals, indicating local, probably non-aeolian, origin for some parna components. As noted previously (see Shepparton Formation), Lawrence (1975) subsequently suggested multiple source,

TABLE 30. ctd.

involving derivation of coarser components by deflation of older fluvio-lacustrine deposits as well as derivation of fine components and calcium carbonate from aeolian dunefields to west.
Stratigraphic nomenclature, synonyms and type section. Named after Widgelli railway station, 10 km east of Griffith N.S.W. (Butler, 1956, 1958; Butler & Hutton (1956). Name Widgelli Pedoderm (Lawrence, 1975) modification of Widgelli parna, and also equivalent to Widgelli Member of Lawrence (1966). Butler (1958) nominated section on eroded bank of Narrancoolambund Lagoon, Lot 63, Parish of Calaragang, County Cooper, N.S.W. as type locality (Fig. 115). Unit also occurs within Goulburn River type section of Shepparton Formation (Fig. 112).
Stratigraphic relationships. Butler (1958) indicated 'Widgelli parna' important marker horizon within upper Shepparton Formation, where disconformable over older near-surface members, and overlain by Mayrung Member.

Unit: Mayrung Member of Shepparton Formation

Age: Late Quaternary

Map symbol: included in TQs

Synonym: Mayrung system

Lithology. Red-brown, grey clay, silty clay, sandy clay, and sand. Sand confined to former channels, whereas dense clay in former floodplain areas. Overlain by range of soil types described as red-brown earths, grey and brown non-calcareous soils. In places soils gypseous and locally saline; concentrations of gypsum blebs some horizons, and calcium carbonate leached to depth of 0.5 m or more (Butler, 1958); mica preserved in less-weathered deeper profiles.
Distribution, thickness and geomorphic expression. Butler (1958) indicated Mayrung Member largely absent over 50–80 km wide zone at margins of Riverine Plain, but beyond this limit deposits coalesce to form almost continuous sheet extending over large tracts of surface of plain. Channels of Mayrung Member incised 6 m into older sediments, but in former floodplain areas only 1–2 m thick. Lawrence (1975) noted Mayrung Member generally absent over Victorian portion of Riverine Plain. Traces of former channels within Mayrung Member identifiable, and raised levee banks commonly preserved (see TQs – 'prior streams').
Environment of deposition. Part of fluvio-lacustrine Shepparton Formation; mixture of channel sands and finer-grained floodplain deposits.
Stratigraphic nomenclature and type section. Named after settlement of Mayrung, 34 km east-northeast of Deniliquin (DENILIQUIN). Hawkins & Beattie (1958) described number of profiles in Lot 59, Parish of Bendigo, County Sturt, N.S.W., which Butler (1958) nominated as type locality of 'Mayrung system'.
Stratigraphic relationship. Eroded into older surface and shallow members of Shepparton Formation, but mainly disconformable over Widgelli Pedoderm. Channel deposits of Mayrung system of Butler (1958) included in 'prior stream' association of Butler (1950).

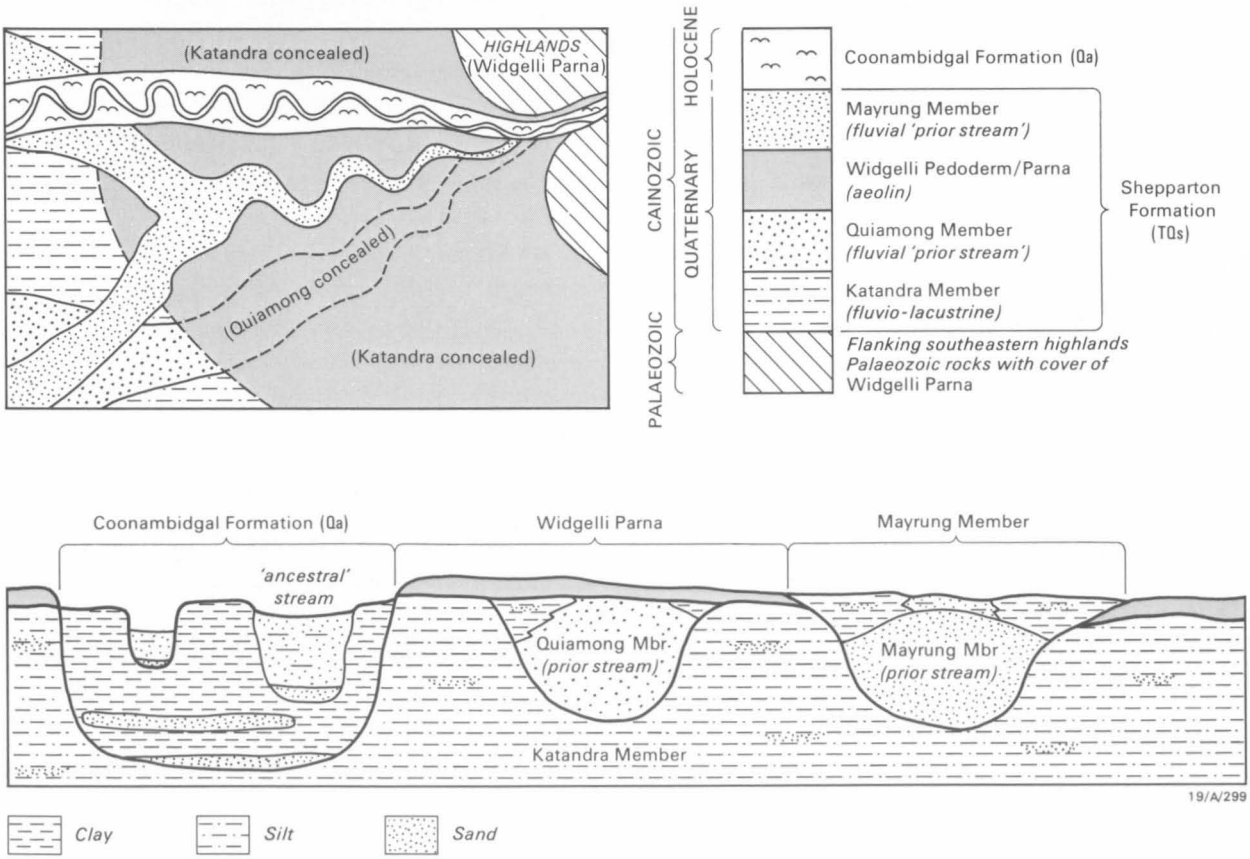


Fig. 114. Stratigraphic relationships (diagrammatic) between surface members of Shepparton Formation; based on Butler (1958) and Schumm (1968a).

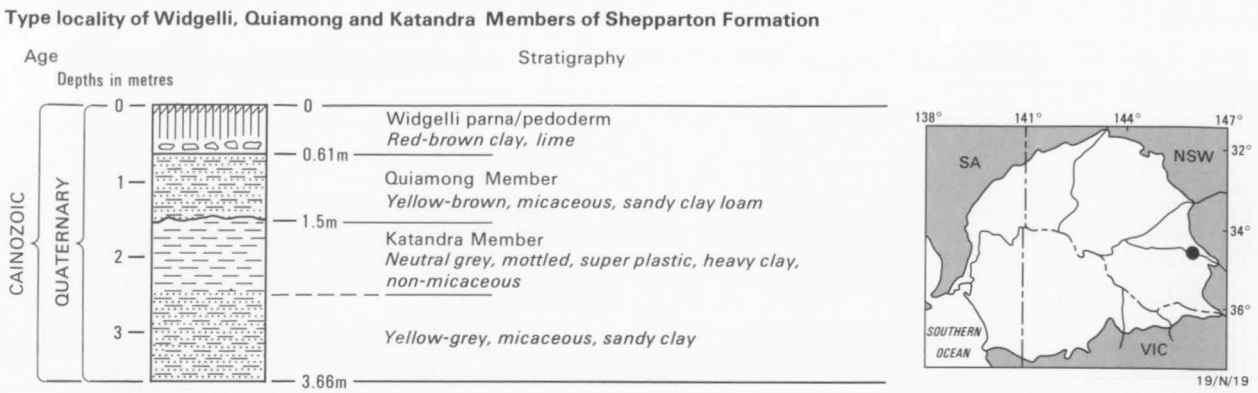


Fig. 115. Type locality of Widgelli parna, Quiamong and Katandra Members of surface and near-surface Shepparton Formation (after Butler, 1958); located on bank of Narrancoolambund Lagoon, adjacent to southwest corner of Lot 63, Parish of Coloragang, County Cooper, 1.5 km north of Darlington Point (NARRANDERA). Lawrence (1966) subsequently converted the depositional units of Butler (1958) into members of the Shepparton Formation.

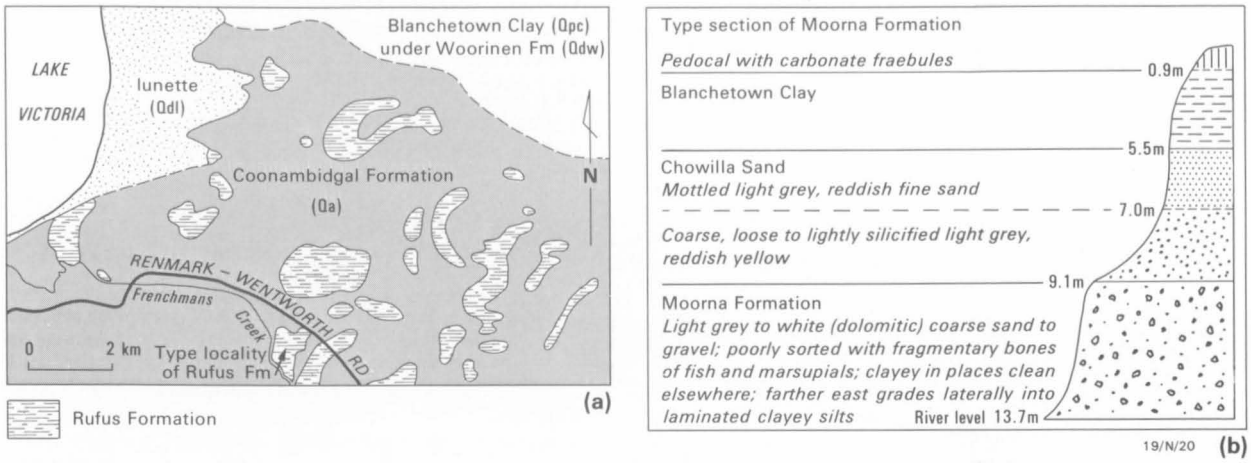
silty loess interbeds ('parna' of Butler, 1956; Butler & Hutton, 1956), which were probably winnowed from the adjacent Quaternary dune complexes of the Mallee landscape to the west (see 'Widgelli Pedoderm', Table 30). Crocker (1946) suggested that the carbonate content of many of the loess veneers of the Mallee was derived from coastal deposits to the southwest, such as those of the Bridgewater Formation and similar sediments of the adjacent marine shelf, exposed to aeolian erosion during periods of lowered sea-level. In contrast, Pels (1964a) and Blackburn (1966a) suggested that the carbonate content of the parna was derived from deflation of local sources within the Riverine Plain. Alternative sources of calcareous materials are also available from the aeolian landscapes to the west. Butler & Hutton (1956) found that particle size within the parna diminished with increasing distance from the Mallee region. The marine shelf was therefore not necessarily the immediate primary source of the carbonate. Calcareous aeolian parna-like deposits are preserved on slopes throughout the highlands of southeastern Australia, and therefore an entirely local origin of the carbonates from local deflation centres is unlikely. Lawrence (1975) subsequently identified several sources of calcareous material, and proposed that all of these may have contributed to the calcareous content of the parna deposits. He commented on the association between the occurrence of aeolian deposits in the Mallee Region and prominent development of calcrete (caliche) horizons. He suggested that aeolian clay particles were derived from erosion of basement, and by deflation of both lacustrine and channel deposits as well as from wind-blown dust from the aeolian terrains to the west. Lawrence (1975) also suggested that the minor sand-sized fraction was incorporated into the parna by saltation or winnowing of local fluvial deposits. Regardless of the source of the calcareous content, the aeolian clay and silt fractions of the parna were probably derived mainly from the aeolian landscapes farther west.

Stratigraphic nomenclature. The Shepparton Formation was named by Lawrence (1966) after the city of Shepparton in BENDIGO, in the southeastern Riverine Plain of northern Victoria.

Synonyms. The name Widgelli Pedoderm of Lawrence (1976a, 1988a; see Table 30) is synonymous with the Widgelli Parna of Butler (1958) and Widgelli Member of Lawrence (1966). Similarly, the Quiamong Member and Katandra Member are, respectively, equivalent, to the 'Quiamong', and 'Katandra' of Butler (1958). The surface traces of former river channels within the Shepparton Formation were referred to as 'prior streams' by Butler (1950).

Type section. Lawrence (1966) nominated a river cliff section on the eroded concave eastern bank of a bend in the Goulburn River at Kialla, 6.5 km south of Shepparton as the type section of the Shepparton Formation (Fig. 112). The type section is representative only of the upper part of the formation, and Tickell (1977a) subsequently established an alternative reference section based on a 110.7 m thick sequence encountered by Narioka No.1 bore (bore No. 1255-1; Fig. 113), located 46 km northwest of Shepparton.

Stratigraphic relationships. The Shepparton Forma-



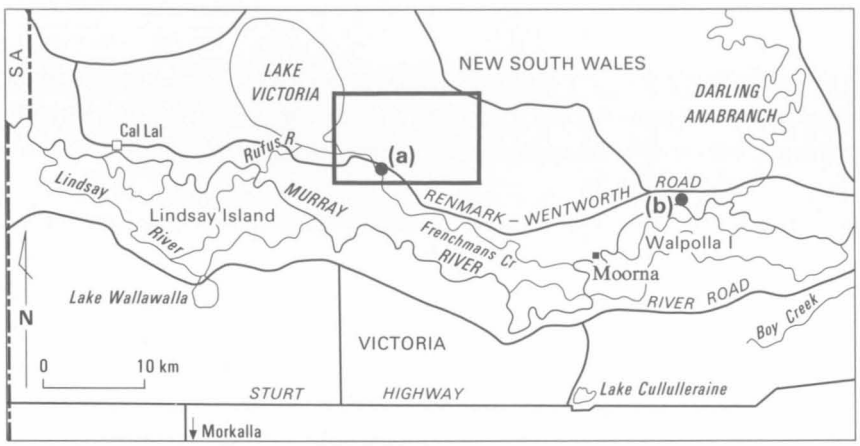


Fig. 116. (a) Type locality of Rufus Formation showing remnants of Pleistocene fluviatile terrace elevated up to 7 m above adjacent alluvium of Coonambidgal Formation, as mapped by Gill (1973a, his fig. 5) – Rufus Formation consists of red/brown mottled sediment, altered by pedogenesis, unlike adjacent greenish-grey sediment of low-lying Coonambidgal Formation.

(b) Type section of Moorna Formation, located at western end of Fisherman's Cliff, Moorna Station, north bank of Murray River (based on fig. 30 of Gill, 1973a).

TABLE 31. PLEISTOCENE CHOWILLA SAND (SHEPPARTON FORMATION EQUIVALENT OF WESTERN MURRAY BASIN)

Unit: Chowilla Sand

Age: Pleistocene

Map symbol: not differentiated from Tps or TQs on enclosed map

Lithology. Eroded lenses of golden yellow, fine to medium-grained, quartz sand (Firman, 1966c, 1973). Grain-size histograms similar to those from underlying Loxton – Parilla Sands (Gill, 1973a).

Distribution and thickness. Identified in cliffs of Murray River, between Merbein in Victoria and Berri in S.A. (Firman, 1973). Thickness highly variable, but up to 10 m recorded.

Palaeontology and age evidence. Diprotodont remains reported (Firman, 1966c). Gill (1973a) and Marshall (1973) found Chowilla Sand preserves remains of fish, tortoise, marsupials, crustaceans and ostracods. Firman (1966c, 1973) suggested Early Pleistocene age, but if correlations of Gill (1973a) correct, then unit is intercalated within Blanchetown Clay, and may range from Late Pliocene to Late Pleistocene in age.

Environment of deposition. At proposed Chowilla damsite (Fig. 87), interpreted by Firman (1973) as fluvial channel sediment derived from weathered surface found between base of Blanchetown Clay and top of Parilla Sand (?Karoonda Surface).

Stratigraphic nomenclature and type section. Named after Chowilla Homestead in County Hamley in southeast CHOWILLA. Cliff sections in Border Gate area designated as type locality.

Stratigraphic relationships. Firman (1971a, 1973) indicated Chowilla Sand occurs at base of Blanchetown Clay, whereas Gill (1973a) included similar sands intercalated within and above Blanchetown Clay, adjacent to Murray River farther east with Chowilla Sand. Lateral equivalent of fluvio-lacustrine Shepparton Formation to east and north, but appears to have been derived from reworking of underlying undifferentiated Loxton – Parilla Sands, and consequently could also be viewed partly as late-stage fluvial component entrenched within that unit. Not differentiated from Loxton – Parilla Sands in boreholes away from Murray River. Appears to be age-equivalent to, and synonymous with, Irymple Member of Blanchetown Clay of Lawrence (1975).

tion forms one of the younger components of the Upper Tertiary to Quaternary fluvio-lacustrine Wunghnu Group. At the margins of the Murray Basin, the formation unconformably onlaps and is flanked by Proterozoic and Palaeozoic sedimentary, metamorphic and granitoid rocks. Locally, the formation disconformably overlies the Olney Formation of the Renmark Group, but mainly conformably overlies and appears to interfinger with the Calivil Formation. The formation is partly stratigraphically equivalent

TABLE 32. PLEISTOCENE RUFUS FORMATION (SHEPPARTON FORMATION EQUIVALENT OF WESTERN MURRAY BASIN)

Unit: Rufus Formation

Age: Late Pleistocene

Map symbol: included in TQs

Lithology. Deeply weathered fine micaceous sand, silt and clay; red towards top, mottled to brown below; overlain by well-developed soil profile with pedogenic carbonates (Gill, 1973a). Red colour and mottled weathering differentiates unit from grey clays of adjacent Coonambidgal Formation.
Distribution and thickness. Remnants of unit identified in stranded fluvial terrace of Murray River, southeast of Lake Victoria (Fig. 116).
Palaeontology and age evidence. Fossil fish, bird egg shells, marsupials, rats; also aboriginal middens, ovens, skeletons. Marshall (1973) described variety of vertebrate remains, including giant marsupials, and left ramus of Sarcophilus laniarius (Tasmanian Devil). Assemblage dated Late Pleistocene.
Stratigraphic nomenclature and type section. Named after Rufus River, which connects Lake Victoria to Murray River in NW MILDURA.
Stratigraphic relationships. Weathered sediments of Rufus Formation form part of stranded Pleistocene fluvial terrace, elevated 7 m above entrenched younger sediments of Coonambidgal Formation. Unlike Moorna Formation and Chowilla Sand, Rufus Formation not predominantly derived from underlying Loxton–Parilla Sands, but lithologically similar to, and stratigraphically equivalent to, Shepparton Formation farther east and north.

to, and partly onlaps the Loxton–Parilla Sands to the west. Macumber (1983) indicated that his basal Yando Member of the Shepparton Formation, for example, is a non-marine lateral facies equivalent of the Loxton–Parilla Sands, and suggested that the ferruginisation in the unit can be correlated with the processes which resulted in development of the ferruginised Karoonda Surface over the top of Loxton–Parilla Sands. At the basin margins, sediments of the Shepparton Formation are locally intercalated with, grade laterally into, and are overlain by coarse colluvial and residual sediments of the Pooraka Formation and other colluvial footslope deposits.

At the western margins of the Riverine Plain and beneath the aeolian plain of the northern Murray Basin, the Shepparton Formation is disconformably overlain by aeolian sediments of the Woorinen Formation, and by sand, silty loess (parna), and clay of Qdp. Within the Riverine Plain and adjacent to the Darling floodplain in the north, the Shepparton Formation is unconformably to disconformably overlain by younger fluvio-lacustrine sediments of the Coonambidgal Formation ('ancestral' and modern river sediments) and other Recent alluvial deposits, deposited mainly within entrenchments incised into the Shepparton Formation. Locally, the formation is also overlain by small discontinuous lacustrine (Ql), source-bordering dune (Qad) and lunette (Qdl) deposits. The prior stream sediments of the Shepparton Formation form the near-surface Quiamong and Mayrung Members of Butler (1958) and Lawrence (1966, 1975), and are entrenched within the Katandra Member.

The stratigraphic relationships between the several geomorphic schemes are not always clear, but, based on the definition of 'Coonambidgal' of Butler (1958), and Coonambidgal and Shepparton Formations of Lawrence (1966, 1975), the 'Coonambidgal I' of Pels (1971) can be correlated with the Shepparton Formation, mainly because it is overlain by a red calcareous soil. Similarly, the Green-Gully/Tallygaroopna Complexes of Bowler (1978a) are bed-load dominated channels, which correlate with the ancestral Coonambidgal I of Pels (1971), but occur beneath a cover of red-brown soil and stratigraphically correlate with the Shepparton Formation. The bed-load dominated channel sands in the southeast possibly also correlate with the sands of the Monoman Formation preserved in the Murray River Gorge at the western margin of the basin. As noted previously, the Coonambidgal Formation is in reality a younger variant of the Shepparton Formation and the distinction between the two units is largely based on geomorphic expression.

Correlative units. The Shepparton Formation of Victoria and New South Wales correlates with the Lower Pleistocene Chowilla Sand (Table 31) of Firman (1973) in the South Australian section of the basin, and with the Upper Pliocene–Lower Pleistocene Moorna Formation (Table 28), and Upper Pleistocene Rufus Formation (Table 32) of Gill (1973a) exposed along the course of the Murray River in MILDURA.

Aquifer characteristics. The fine to coarse sand bodies of the Shepparton Formation form an aquifer system, consisting of semi-confined shoestring sand bodies with varying degrees of lateral and vertical interconnection (see 'Groundwater'). The aquifer system is of major importance in the eastern and southeastern Riverine Plain. Groundwater mounds have developed beneath some irrigation areas, resulting in waterlogging of root systems and local salinisation problems. In New South Wales, the aquifer system is used for stock and domestic purposes east of Hay.

Economic geology. In areas near the larger settlements, small sand pits in the former prior stream channels provide material for local road-paving and concrete aggregate.

Data sources. Stratigraphic descriptions of the Shepparton Formation are given in Lawrence (1966, 1975, 1976a, 1988a), Woolley (1978), Woolley & Williams (1978). Borehole sections are described in Tickell (1977a) and Tickell & Humphrys (1979, 1980). Geomorphic descriptions of the present surface of the Riverine Plain, with emphasis on the morphology of prior stream deposits, are recorded in Butler (1950, 1956, 1958, 1959, 1960, 1961), Gill (1955a), Butler & Hutton (1956), Hawkins & Walker (1956), Langford-Smith (1958, 1959, 1960,a,b, 1962, 1966), Stannard (1962), Cotton (1963), Drury (1963), Pels (1960a, 1964a,b, 1966, 1969a,b, 1970, 1971), Cockroft (1965), Bowler (1966a,b, 1967, 1978a), Bowler & Harford (1966a,b), Bowler & Macumber (1967, 1968), Macumber (1968, 1969), and Schumm (1968a,b), Butler & others (1973), Bowler & Wasson (1984). Hydrogeological characteristics of the formation are described in Lawrence (1975), Tickell (1977a), and Tickell & Humphrys (1979, 1980, 1987). Soil profiles and the regional distribution of various soil types are described in Skene & Freedman (1944), Butler (1958, 1960, 1961), as well as in a number of CSIRO soil survey reports.

Members of the Shepparton Formation

Butler (1958) identified five surface or near-surface depositional units during the course of CSIRO mapping of the distribution of soil types in the Riverine Plain in New South Wales and northern Victoria (Fig. 114). The oldest is the 'Katandra riverine deposit', which consists of mixed fluvial channel and floodplain deposits, and includes some aeolian sediments. The overlying 'Quiamong riverine deposit' is entrenched within the Katandra unit and is the oldest component of the prior stream association, and comprises channel sands. The Katandra and Quiamong units are both overlain by a blanket of 'Widgelli parna' (aeolian clay; Butler & Hutton, 1956). These units are further entrenched by a younger prior stream depositional unit – the 'Mayrung riverine deposit', also mainly channel sands. The modern channel, and associated restricted floodplain deposits (including abandoned 'ancestral streams' of Pels, 1964b, 1966) form the 'Coonambidgal riverine deposit'. These units have been identified on soil maps of several extensive areas, but it is not yet known if they are representative of the entire Riverine Plain.

In northern Victoria, Lawrence (1966) subsequently subdivided the Shepparton Formation of the southeastern Riverine Plain into a number of members based partly on modifications of the above soil-stratigraphic depositional systems of Butler (1958), and partly on recognition of at least one new unit below the Katandra Member – the Kialla Member (Table 30). These members are restricted to the upper surface or near-surface levels of the Shepparton Formation. The younger of these shallow members forms much of the present surface of the Riverine Plain, whereas the older members are only locally exposed. Lawrence (1966, 1975, 1976a, 1988a) recognised four of the members in his type section of the Shepparton Formation (upper Shepparton Formation), located on the east bank of the Goulburn River, near the southern boundary of Allotment 59, Parish of Kialla, 6.5 km south of Shepparton on BENDIGO. The section is capped by the Widgelli Pedoderm underlain by the Quiamong, Katandra and Kialla Members (Fig. 112). The Kialla/Katandra and Katandra/Quiamong Members are separated by buried palaeosols. The Mayrung Member is absent from the top of the section.

A regional stratigraphic subdivision of the Shepparton Formation in the subsurface has not yet been achieved. Tickell (1977a) recognised five sandy members of only local extent within the Shepparton Formation, in a number of borehole sections within the Campaspe, Goulburn, and Ovens valleys (Laceby Gravel Member, Yielima Member, Yalca Member, Waaia Member, and Barwo Member). Each of these members is intercalated within clays of the Shepparton Formation, and is generally not in contact with the underlying or overlying sand member. It should be noted, however, that the regional continuity of these local member units is limited, and Tickell & Humphrys (1987) subsequently indicated that the subdivision is not regionally applicable. Pels (1960a) recognised three similar local sand-dominated intervals within the Quaternary alluvial sediments near Griffith to the north, but again their applicability in other areas of the basin has not yet been tested.

Upper Pliocene–Quaternary Shepparton Formation equivalents of the western Murray Basin

The Shepparton Formation is confined mainly to the northern and eastern Murray Basin. Time-equivalent fluvial sediments were, however, deposited in western areas. These include the previously

described fluvial components of the undifferentiated Loxton–Parilla Sands, and fluvial Upper Pliocene Parilla Sand exposed by the Murray River in South Australia, northwest Victoria and southwestern New South Wales. Younger equivalents include poorly known formations which are exposed in cliffs of the Murray River: Late Pliocene to ?Early Pleistocene Moorna Formation (Table 28), Pleistocene Chowilla Sand (Table 31), and the Late Pleistocene Rufus Formation (Table 32). Firman (1973) placed the Chowilla Sand stratigraphically below the Blanchetown Clay, whereas Gill (1973a) included sands intercalated within the Blanchetown Clay in the Chowilla Sand. These latter occurrences are therefore the age-equivalent to, and synonymous with, the Irymple Member of the Blanchetown Clay (Table 33). The above units occur stratigraphically below, within, and above the Plio-Pleistocene Blanchetown Clay, and are all age-equivalent to the fluvial Shepparton Formation farther east and north. As noted previously (see 'Loxton–Parilla Sands'), the distributions and interrelationships between these units are poorly known, and they cannot be distinguished on drillers logs beyond the type areas exposed by the Murray River. The Moorna Formation of Gill (1973a), for example, is not readily differentiated from the Loxton–Parilla Sands, and has not been identified in the subsurface.

Unit: Undifferentiated Duricrust
Age: Late Tertiary to Quaternary
Map symbol: TQl
Informal nomenclature: 'Ironstone', 'Duricrust', 'Laterite'

Lithology. 'TQl' is a composite unit comprising a variety of ferruginous, pisolithic duricrusts, and lateritized, deeply weathered basement. It is locally underlain by mottled clay, over a pallid zone of white, kaolinitic clay. Minor silcrete on the northwestern margin of the Murray Basin have also been included in this unit.

Distribution, thickness, and topography. TQl is distributed around the margins of the Murray Basin, where it forms residual, flat to gently undulating pedogenic surfaces. It is best developed on the Dundas Tableland of western Victoria, and in the Mount Lofty, Flinders, and 'Olary' Ranges in South Australia. Thicknesses of these duricrusts are highly variable, and many are underlain by deep weathering profiles tens of metres thick. The laterites of the Dundas Tableland are up to 10 m thick, consist of resistant ironstone layers underlain by mottled and pallid zones, and overlie a variety of rock types including Pliocene sands (Gibbons & Downes, 1964; Gibbons & Gill, 1964). Ferruginous and siliceous pedogenic surfaces within the Murray Basin, such as the Karoonda Surface overlying the Pliocene Loxton–Parilla Sands, are equivalents of TQl. The Karoonda Surface is less than one metre thick, and locally crops out in the Murray River cliffs (see 'Loxton–Parilla Sands'), where it consists of pisolitic iron segregations cemented by opaline silica, underlain by mottled and pallid zones with kaolin and gibbsite.

Stratigraphic relationships and age evidence. TQl duricrusts have developed upon a wide variety of pre-Cainozoic basement rock types, and are of varying ages. The laterite of the Dundas Tableland developed over rocks ranging in age from Cambro-Ordovician to Early Pliocene (Abele & others, 1976, 1988). The laterite may be a composite of several phases of lateritization and may have developed over a long period (Gill, 1958, 1964), but formation of a major component appears to have followed uplift of the Dundas Plateau in the Pliocene. The Karoonda Surface (Karoonda Soil of Firman, 1966c) overlies Pliocene Loxton–Parilla Sands and underlies Late Pliocene–Pleistocene Blanchetown Clay. The age of lateritic duricrust in the South Australian ranges has been the subject of debate. Alley (1977a,b) thought that laterite in these ranges was of Eocene and Miocene age, citing stratigraphic evidence of laterite overlain by dated sediments, in the small Wakefield Basin. McGowran & others (1977) disagreed with Alley's (1977a) evidence, and were of the opinion that lateritization may well have occurred in pre-Eocene times, citing evidence from elsewhere in South Australia. Within the Murray Basin, calcretes (Qca) have dominated western areas for at least the past 0.5 Ma, and Bowler (1982) suggested that a shift from ferruginous/silica-dominated laterites, such as the Karoonda Surface, to calcrete-dominated profiles, reflected increasing aridity associated with the northward drift of he Australian continent in the Late Cainozoic.

Characteristics and environment of formation. TQl lateritic duricrusts are characterised primarily by lithology. Secondary characteristics for most TQl occurrences are geographic location at the basin margins, and stratigraphic position, often over pre-Cainozoic basement. The TQl duricrusts were formed by deep weathering and pedogenesis, and are thought to have formed during periods of warm humid, but seasonally arid, climates (Bowler, 1982). The chemical mobilization of iron and silica in the

Pliocene contrasts with the carbonate-dominated, Quaternary weathering profiles associated with the overlying aeolian Mallee landscape (see 'Woorinen Formation' and 'Calcretes').

Data sources. Descriptions of duricrust deposits of the Murray Basin region are recorded in Gill (1958, 1964), Gibbons & Downes (1964), Gibbons & Gill (1964), Firman (1964, 1965a, 1966c, 1971a, 1973), Twidale & Bourne (1975), Abele & others (1976, 1988), Alley (1977a,b), McGowran & others (1977), Bowler (1980, 1982), and Milnes & others (1985).

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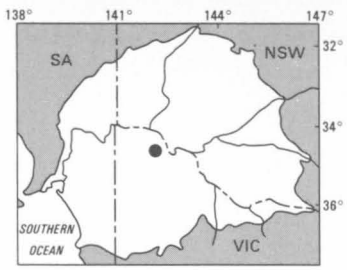


Fig. 117. Mound of ferricrete-cemented sand at Raak Plains groundwater discharge complex (MILDURA); formed by precipitation of iron from acid groundwater at point of discharge into alkaline saline lake waters.

CAINOZOIC STRATIGRAPHY — QUATERNARY UNITS

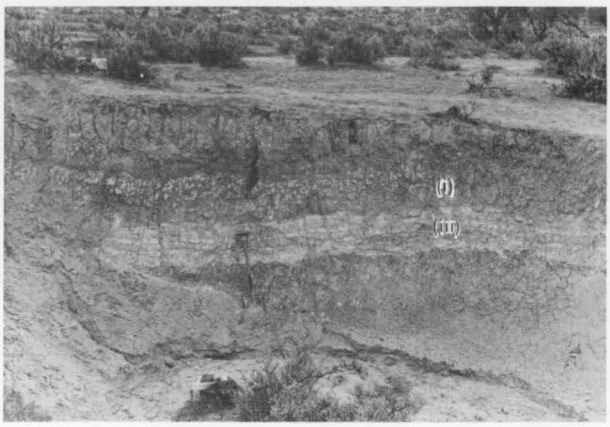
Thin Quaternary units mantle almost the entire surface of the Murray Basin. At the basin margins, they include fanglomerate and colluvial deposits of the Pooraka Formation. In the east, they consist of fluvio-lacustrine sediments of the Shepparton Formation (described in the previous chapter), and the Coonambidgal Formation and other deposits of the entrenched modern river systems. In the west, lacustrine sediments of the Pleistocene Blanchetown Clay underlie a thin veneer of aeolian and associated saline lacustrine deposits. Quaternary units in coastal areas are mainly associated with stranded beach-ridge, inter-ridge fluvial, lacustrine and lagoonal environments. As noted previously, many of the surficial units of the Murray Basin are essentially morphostratigraphic in character rather than conventionally lithostratigraphic.

Unit: Blanchetown Clay
Age: Late Pliocene to Early Pleistocene
Map symbol: Qpc
Component unit: Irymple Member (Table 33)
Associated unit: Bungunnia Limestone (Table 34)

Lithology. The Blanchetown Clay consists of greenish grey, red-brown or variegated, silty to sandy clay, with many local variations in lithology. It contains thin beds of quartz sand and some thin micrite lenses, and is commonly gypsiferous near the top (Fig. 118). Gypsiferous, siliceous, and impure cal-

(a)

(b)



(c)

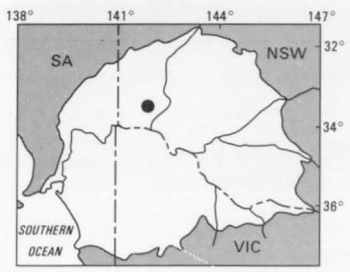


Fig. 118. Blanchetown Clay (Qpc) exposed at southwest margin of Lake Milkengay, adjacent to Darling Anabranch (ANABRANCH): (a) crystalline 'chickenwire' gypsum infilling veinlets within well organised coarse blocky clay in near-surface layer (i) of (c).

(b) Erosional gully exposing large crystalline concretions of gypsum (ii) within upper Blanchetown Clay; light coloured band (iii) consists of interlaminated silt and silty clay; dry bed of Lake Milkengay in background.

(c) Thin layer of red sand, clay pellets, and poorly developed soil (Qdp) overlying Blanchetown Clay with gypsum-rich bed (i) and silty bed (iii) – scale provided by shovel in left-centre.

TABLE 33. PLEISTOCENE IRYMPLE MEMBER OF BLANCHETOWN CLAY

Unit: Irymple Member of the Blanchetown Clay

Age: Pleistocene

Map symbol: included in Qpc

Lithology. Lawrence (1972, 1975), and Lawrence & Goldberry (1973), described number of sections of Blanchetown Clay containing Irymple Member; including type locality consisting of clayey, mottled, ferruginous, dark-red to yellowish-brown sandstone. Sand well-sorted, fine-grained, with kaolinitic matrix; ironstone concretions present.

Distribution and thickness. Associated with Blanchetown Clay along course of Murray River, northwest Victoria, from Robinvale to S.A. border. Type section 10 m thick.

Palaeontology and age. Mainly of Early Pleistocene age – based on relationship with Blanchetown Clay, but may extend from latest Pliocene to early Late Pleistocene.

Interpreted environment of deposition. Fluvial deposit, probably partly derived from weathered zone of underlying Loxton–Parilla Sands (Lawrence, 1975, 1976a).

Stratigraphic nomenclature and type section. Named after township of Irymple. Type section in cliff section of Murray River, at Red Cliffs Pumping House, where occurs 7 m from top of river cliff, beneath Blanchetown Clay and directly over Loxton–Parilla Sands.

Stratigraphic Relationships. Occurs as sandy unit, intercalated mainly within lower Blanchetown Clay (sand less common in upper Blanchetown Clay). Locally disconformable over Loxton–Parilla Sands. Firman (1966c, 1973) described Chowilla Sand as bright yellow, poorly sorted fluvial sand underlying Blanchetown Clay (see Table 31), whereas Gill (1973a) correlated sands intercalated within Blanchetown Clay with Chowilla Sand – thus Chowilla Sand of Gill (1973a) (within Blanchetown Clay) equivalent to, and probably synonymous with, Irymple Member of Blanchetown Clay of Lawrence (1972).

careous septarian nodules, and ostracod sands occur locally. In South Australia, coarse-grained sand and gravelly outwash deposits have been included in the Blanchetown Clay. Gill (1973a) recorded the presence of white fine-grained dolomite and sandy dolomite.

At the top of the unit in western areas of the basin, a dolomitic limestone is differentiated as the Bungunnia Limestone (Table 34). Gill (1973a) correlated intercalated sand units with the Chowilla Sand (Table 31), whereas Lawrence (1975) placed these in the Irymple Member of the Blanchetown Clay (Table 33).

Distribution and thickness. The distribution of the Blanchetown Clay (Fig. 119) is patchy, being heavily constrained by the Late Pliocene topography of the western Murray Basin (Stephenson, 1986). The unit locally attains a thickness in excess of 20 m, but one of a few metres is more common.

Geometry and topography. The geometry of the Blanchetown Clay is partly a product of the topography at the time of deposition, and partly due to post-depositional erosion. It has both an irregular lower surface, because it was deposited unconformably over an undulating geomorphic surface (Stephenson, 1986), and a locally irregular upper surface due to erosion (Rogers, 1978). The Blanchetown Clay is normally covered by younger, mainly aeolian sediments, but is exposed in cliffs adjacent to the Murray River (Fig. 88), the Darling River, and some lakes (e.g. western shore of Lake Victoria). In places, it is exposed by washouts in areas of higher elevation, or by the activities of man (such as in Lake Cawndilla's outlet channel).

Palaeontology. The Blanchetown Clay preserves the remains of several genera of freshwater ostracods (McKenzie & Gill, 1968; Gill, 1973a), which locally form almost pure ostracod sands. Gill (1973a) also recorded locally abundant *Corbicula*, as well as fish spines, vertebrae and bones of a large marsupial. Lawrence & Goldberry (1973) recorded the presence of worm tubes and crustacean fragments within the Blanchetown Clay, together with the fish *Neoceratodus*, but the overall fauna of the lacustrine sediments has yet to be formally described.

Age evidence. Bowler (1980) used magnetic reversal stratigraphy to establish that the oldest part of Blanchetown Clay was more than 2.4 Ma old, and that the youngest sediments were less than 0.7 Ma old. These results have been confirmed and extended at the proposed Chowilla dam site and at Lake Tyrrell by An Zhi–Sheng & others (1986). Stephenson (1986) showed that a continuous gradation from the Blanchetown Clay to modern lake sediments occurred in some lakes in the western Murray Basin.

Characteristics. The Blanchetown Clay is characterised by its lithology and stratigraphic position, and is readily distinguished from most other units in the Murray Basin. It could be confused with the Shepparton Formation, but the two are mainly geographically separated; the fluvial Shepparton Formation is also normally sandier than Blanchetown Clay. In South Australia, outwash deposits from the ranges have been included within the Blanchetown Clay (Rogers, 1978), making it locally difficult to distinguish from the Pooraka Formation.

In the area around Bordertown (NARACOORTE), an aeolian sand overlies Parilla Sand and underlies a clay unit which Firman (1973) correlated with the Blanchetown Clay; however, this clay unit cannot have been part of the Blanchetown Clay because of its geographic position (Stephenson, 1986), but can be correlated with the Shepparton Formation.

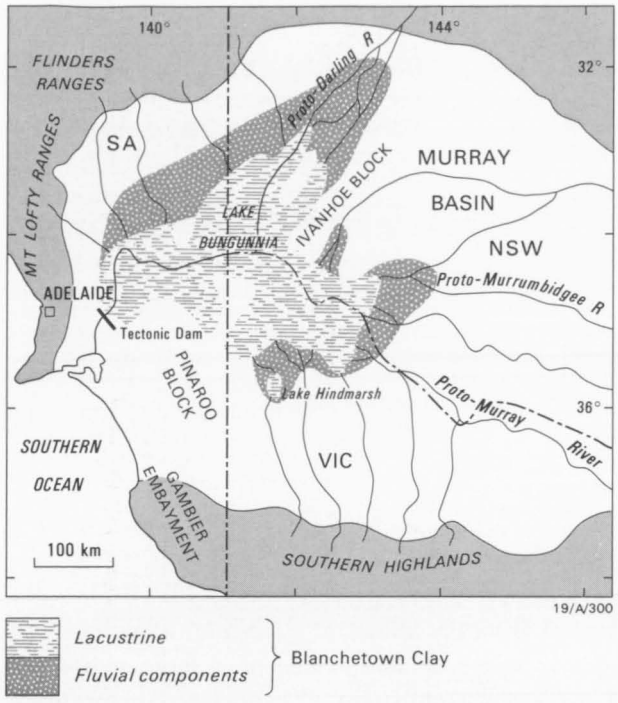


Fig. 119. Greatest extent of ?Upper Pliocene–Pleistocene Lake Bungunnia, and distribution of Blanchetown Clay (Qpc), including possible distribution of fluvial components (after Stephenson, 1986).

Environment of deposition. The unit was deposited under fluvio-lacustrine conditions, with most sedimentation taking place in a large freshwater body known as Lake Bungunnia (Firman, 1965a, 1973). Lake Bungunnia was formed by tectonic damming of the ancient Murray river at about 2.5 Ma ago, and had a maximum extent of over 33 000 km^2 (Stephenson, 1986). The lake was shallow, with a maximum depth of less than 70 m, and minor climatic fluctuations caused large shoreline migrations and complex interfingering of lacustrine and fluvial components of the Blanchetown Clay near lake margins (Stephenson, 1986). The interpreted relative distribution of the lacustrine and fluvial components of the Blanchetown Clay as shown in Figure 119 is a generalization only, as shoreline fluctuations caused extensive interfingering. Gypsiferous sediments at the top of Blanchetown Clay can be related to the emptying and drying of Lake Bungunnia some 0.6 Ma ago: as water levels fell, Lake Bungunnia split into several smaller lakes, some of which did not have significant water intake, and thus developed hypersaline conditions, with the consequent deposition of gypsum. The Blanchetown Clay suffered local erosion shortly after deposition (Roberts, 1968a; Rogers, 1978).

The interrelationships between the Blanchetown Clay, the Bungunnia Limestone, and Lake Bungunnia have been discussed by Stephenson (1986). Study of the Plio-Pleistocene lacustrine system in which Blanchetown Clay was deposited has indicated that climatic conditions at that time were at least twice as wet as those of today: an average rainfall over the Murray–Darling catchment of at least 500 mm/yr was likely. Lake Bungunnia could not have existed under present climatic conditions. Stephenson (1986) proposed two 'end-member' models of Lake Bungunnia's history, and related these to the sedimentological features of the Blanchetown Clay and the Bungunnia Limestone.

The demise of Lake Bungunnia heralded the onset of aridity in southern Australia (Bowler, 1980, 1982), and many modern landforms date from that time. Modern salt lakes in parts of the western Murray Basin (on ANABRANCH, for example) may be directly descended from Lake Bungunnia, so that in these areas the boundary between the Blanchetown Clay and the halite and gypsum of the overlying Yamba Formation can be regarded locally as transitional (Stephenson, 1986), and the Blanchetown Clay may be some hundreds of thousands of years younger in these areas than in most other locations.

Stratigraphic nomenclature. The Blanchetown Clay is named after the town of Blanchetown, County Albert, South Australia. The name follows the informal usage of Spence (1958), and was formalized by Firman (1965a, 1973).

Type section. The type section of the Blanchetown Clay was designated by Firman (1973) as "three miles below Blanchetown on the left bank" (i.e. 5 km south of Blanchetown on the west bank of the Murray River). Firman (1973) also designated a supplementary section situated "on the mesa edge and in an adjoining dam adjacent to Bungunnia Homestead about 10 miles north of Morgan".

Stratigraphic relationships. The Blanchetown Clay unconformably overlies Pliocene Loxton–Parilla Sands and Norwest Bend Formation, and locally directly overlies Miocene limestone (Pata Limestone, Morgan Limestone) and parts of the Shepparton Formation. It also disconformably overlies a 'mid-Pliocene' weathering/pedogenic surface (the Karoonda Soil/Surface) at some localities, such as the proposed Chowilla Dam Site and Lake Tyrrell (Bowler, 1980). It interfingers with and is overlain by both the Bungunnia Limestone and the Shepparton Formation. It is disconformably to unconformably overlain by younger lacustrine (Ql – Yamba Formation), riverine (Qa – Coonambidgal Formation),

TABLE 34. PLEISTOCENE BUNGUNNIA LIMESTONE

Unit: Bungunnia Limestone

Age: Early Pleistocene

Map symbol: included in Qpc (Blanchetown Clay)

Lithology. Well-cemented, flaggy, dolomitic limestone, consisting of laminated micrite, oomicrite, oolitic and pisolitic calcarenite, oolitic algal biolithite. Composed almost entirely of carbonate. Distinctive laminated to oolitic structure, in both outcrop and thin section (Fig. 120).

Distribution and thickness. Restricted to west Murray Basin, mainly on RENMARK and CHOWILLA in S.A. (Firman, 1972; Rogers, 1978); also in few locations on MILDURA (Lawrence & Goldberry, 1973). Patchy unit of variable thickness, normally ranging up to 3 m (Firman, 1972), although isolated thicknesses of 5 m recorded (Brown & Stephenson, 1986).

Palaeontology and age evidence. Abundant algal material; ostracods locally present. Neither fauna nor flora formally described. Bungunnia Limestone and Blanchetown Clay closely related units – Gill (1973a) described similar, but thin, dolomitic units within Blanchetown Clay at sites along Murray River in NW Victoria, and noted abundant presence of ostracods Ilyocypris, Candona and Diacpris. Bungunnia Limestone deposited late in history of Lake Bungunnia, which existed approximately 2.5–0.6 Ma (Stephenson, 1986). Earliest date for Bungunnia Limestone deposition uncertain, but Stephenson's (1986) model of Lake Bungunnia suggests chemical/algal activity in west of lake peaked between 1.2–0.6 Ma, and likely that limestone deposited at that time.

Characteristics. Lithology, geographic location, and stratigraphic position. Only lithologically similar unit in Murray Basin is unnamed lagoonal dolomites of Buccleuch Embayment (Qpu), which are unrelated to Lake Bungunnia and Bungunnia Limestone.

Environment of deposition. Deposited towards west of large, shallow, fresh water Lake Bungunnia, which covered much of west Murray Basin in latest Pliocene and Early Pleistocene. Lake formed when tectonic damming blocked course of ancient Murray River and cut off access to Southern Ocean. Bungunnia Limestone deposited late in clastic-starved west parts of lake. Stephenson (1986) discussed several possible mechanisms for demise of Lake Bungunnia some 0.6 Ma ago, but regardless of which is most likely, deposition of Bungunnia Limestone ceased at about that time.

Stratigraphic nomenclature and type section. Named after Bungunnia Homestead, 16 km north of Morgan in S.A. by Firman (1965a, 1973), who also designated type section as "mesa edge adjacent to Bungunnia Homestead". Firman (1973) regarded Bungunnia Limestone as distinct stratigraphic unit, but could be regarded as member of Blanchetown Clay.

Stratigraphic relationships. Conformable over, and locally interfingers with, upper Blanchetown Clay. Locally unconformable over Loxton–Parilla Sands or Murray Group limestones, but more commonly Blanchetown Clay separates it from these older units. Disconformable under variety of post-Lake Bungunnia sediments, including younger lacustrine deposits (Ql, and Yamba Formation), alluvium (Recent Qa, and Shepparton Formation), colluvium (Pooraka Formation), and aeolian sands (Qdp, and Woorinen Formation). Locally developed calcrete cap, particularly north of North West Bend (CHOWILLA; Rogers, 1978).

Correlations. Part time-equivalent to Shepparton Formation and lower part Pooraka Formation. Possibly part time-equivalent to Qpu lagoonal dolomites of Buccleuch Embayment (Rogers, 1980a), but probably younger than Coomandook Formation, although age control on latter unit poor.

Hydrogeology. Local aquitard below perched aquifers in overlying Quaternary sands, but too patchy to be significant, and above groundwater table in area of occurrence.

Data sources. Firman (1965a, 1972, 1973), Lawrence & Goldberry (1973), Rogers (1978), Stephenson (1986).

and aeolian sediments (Qdw – Woorinen Formation; Qdp, and Qdu) sediments. It is also unconformably overlain by Pooraka Formation and other outwash deposits, and by calcretes.

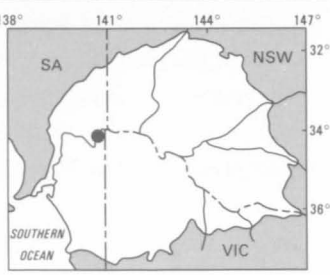


Fig. 120. Bungunnia Limestone with pisolitic and oolitic concretions; from cliff top at north bank of Murray River at Spring Cart Gully (RENMARK).

Correlations. The top of the Blanchetown Clay is a facies equivalent of the Bungunnia Limestone, and possibly of elements of the Yamba Formation. The Blanchetown Clay is a partial time-equivalent of the fluvial Shepparton Formation, and of the fluvial to colluvial Pooraka Formation; it is also a partial time-equivalent of several coastal formations of the Buccleuch and Gambier Embayments, including the Coomandook Formation, Qpu, and the older parts of the Bridgewater Formation and the Padthaway Formation.

Hydrogeology and economic geology. The Blanchetown Clay locally acts as an aquitard, but because of its patchy distribution is of little importance in the hydrogeology of the Murray Basin as a whole. Sands overlying the Blanchetown Clay locally form perched aquifers. The unit forms a low permeability seal under many of the evaporation basins used for the disposal of saline surface and groundwater. The upper part of the Blanchetown Clay is often gypsiferous, and pure deposits have been mined, particularly near Blanchetown (RENMARK). Gypsum from the Blanchetown Clay has also been reworked into younger deposits of the Yamba Formation (Firman, 1973).

Data sources. For descriptions of the Blanchetown Clay, see Spence (1958), Firman (1965a, 1973), Mc-

Kenzie & Gill (1968), Gill (1973a), Goldberry & Oliver (1973), Lawrence & Goldberry (1973), Rogers, (1978), Bowler, (1980), An Zhi—Sheng & others (1986), and Stephenson (1986).

Unit: Coomandook Formation
Age: Early Pleistocene
Map symbol: Qpl

Lithology. The Coomandook Formation is a partly lithified grey or cream fossiliferous calcarenite, with medium-grained quartz sand, calcareous sand, sandy clay, lithic clasts (mainly limestone), and calcareous skeletal debris. It is largely, but not completely, composed of material reworked from the older Murray Group limestones (in particular the Gambier Limestone, the Mannum Formation, and the Morgan Limestone); and most of its carbonate content is reworked skeletal material (Firman, 1967b; Rogers, 1980a). Although many borelogs refer to the formation as a 'sandy limestone' (O'Driscoll, 1960), the carbonate of the Coomandook Formation is mainly clastic rather than chemical in origin. It also contains some fine-grained clay and silt, which were presumably of contemporaneous rather than reworked origin.

Distribution, thickness, and geometry. The Coomandook Formation is restricted in distribution to parts of the Buccleuch and Gambier Embayments (Fig. 55): it occurs to the southwest of a line joining the towns of Coomandook and Naracoorte, and extends at least to the coast (Fig. 121). At the time of deposition of the Coomandook Formation, the Padthaway Ridge formed a chain of granite islands (Rogers, 1980a), and the formation is particularly thick (up to 75 m) to the west of this archipelago; elsewhere, thicknesses of several tens of metres are typical, although the unit is progressively less thick to the east (Brown & Stephenson, 1986). The geometry of the Coomandook Formation is thus wedge-shaped, with the thin edge in the east, modified by the effects upon sedimentation patterns of the buried topography of the underlying Padthaway Archipelago.

The Coomandook Formation is probably entirely concealed. Rochow (1969) showed outcrops of '?Coomandook' on the north of the NARACOORTE 1:250 000 geological map, but noted that these sediments were commonly covered by a veneer of Molineaux Sand. In contrast, Rogers (1980a) did not show Coomandook Formation cropping out on the adjoining PINNAROO geological map. Therefore, although it is possible that the Coomandook Formation locally crops out on NARACOORTE, the area concerned is shown as Molineaux Sand overlying Coomandook Formation on the enclosed 1:1 000 000 geological map.

Palaeontology and age evidence. The fauna of the Coomandook Formation is dominated by reworked, and often abraded, fossils from the Murray Group limestones. In addition, it has a comparatively sparse contemporary fossil assemblage, including the pelagic marine gastropod *Hartungia*, which indicates an Early Pleistocene age (Ludbrook, 1978). However, there is a lack of diagnostic microfossils in the standard subsurface section (Rogers, 1980a), and it may include sediments of Pliocene age at its base. The stratigraphic relationships with unnamed Qpu and Bridgewater Formation, which overlie Coomandook Formation, suggest that the unit is unlikely to be younger than 0.9 Ma old.

Characteristics. The Coomandook Formation is characterised by its stratigraphic and geographic positions, its lithology, and by the abundance of skeletal debris reworked from older limestones. In some borehole logs, it is difficult to distinguish from the Murray Group limestones. However, the Coomandook Formation is generally sandier and more poorly consolidated than the older limestones, and can also be distinguished from those units where it contains clay or silt. Similarly, the Coomandook Formation can be distinguished from the younger Qpu lagoonal dolomite by the cementation and algal structures common in the latter, as well as by geographic and stratigraphic position. The Coomandook Formation and the Bridgewater Formation are difficult to tell apart in some borelogs, but the former has much more skeletal material than the latter. The Coomandook Formation is distinguished from most younger units by lithology.

Our knowledge of the Coomandook Formation has been restricted by its localised, subsurface occurrence, so that in most borehole logs it is referred to, at best, as a 'Pleistocene sandy limestone' (cf. O'Driscoll, 1960); the drilling of a fully cored stratigraphic hole at some future date would greatly increase understanding of this formation.

Environment of deposition. The Coomandook Formation was deposited during an Early Pleistocene (and possibly latest Pliocene) marine incursion into the Buccleuch Embayment, at the southwestern margin of the Murray Basin (Fig. 121). The severe erosion suffered by the underlying Murray Group limestones suggests that the Coomandook Formation was deposited in a high-energy, shallow-marine shelf environment; Firman (1973) suggested that parts of

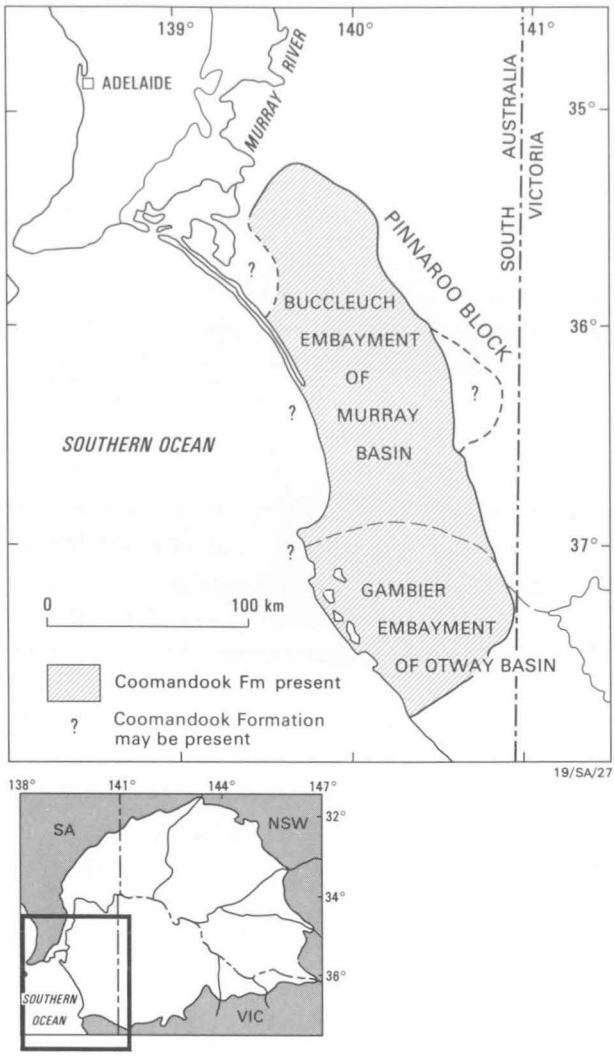


Fig. 121. Approximate area of distribution of Coomandook Formation (Qpl); distribution of formation poorly known because entirely subsurface; it locally onlaps concealed granitic highs of Padthaway Ridge, and may extend offshore.

the Coomandook Formation are of littoral origin. An endemic benthic fauna has not been identified in the Coomandook Formation (except for benthic foraminifera), suggesting perhaps that the environment for filter feeding organisms, in particular, was hostile, probably because of a constantly agitated substrate. This in turn suggests very shallow water, although sediment to the west of the Padthaway Ridge, where the Coomandook Formation is thickest, may have been transported a considerable distance from the erosional loci.

Stratigraphic nomenclature and type section. The Coomandook Formation is named after the town of Coomandook, County Buccleuch, South Australia; as it is not certain that the Coomandook Formation crops out, there is no surface type section. The standard subsurface section is Bore No. 6827-0257, in Section 308A, Hundred of Peake, County Buccleuch (Firman, 1967b). Cuttings are held in the South Australian Department of Mines (Firman, 1973).

Stratigraphic relationships. The Coomandook Formation disconformably to unconformably overlies the Oligocene to Miocene Murray Group limestones. In most cases, the Morgan Limestone and the Mannum Formation have been completely eroded, so that the Coomandook Formation overlies remnants of the Gambier Limestone; however, at the landward margins of its distribution the Coomandook Formation can overlie the Mannum Formation or the Morgan Limestone. Rarely, the Coomandook Formation can directly, and unconformably to disconformably, overlie the Oligocene Ettrick Formation.

The Coomandook Formation is disconformably overlain by younger Pleistocene units, such as the Bridgewater Formation, Qpu, and the Padthaway Formation. It is also disconformably overlain by Recent units, such as the Molineaux Sand, and Qfr outwash deposits from the Marmon Jabuk Scarp.

Correlations. Within the Murray Basin, the Coomandook Formation is partly time equivalent to the Blanchetown Clay and the Shepparton Formation.

Hydrogeology. The Coomandook Formation locally forms an aquifer in NARACOORTE and PINNAROO.

Data sources. Descriptions of the Coomandook Formation are to be found in publications by O'Driscoll (1960), Firman (1967b, 1973), Rochow (1969), and Rogers (1980a).

Unit: Pooraka Formation and other undivided colluvial and residual deposits
Age: Quaternary, Early Pleistocene to Holocene; Pooraka Formation itself is mainly Late Pleistocene
Map symbol: Qfr
Synonyms: Pooraka Clay
Associated units: Tawonga Gravels, Callabona Clay, Telford Gravel

Lithology, distribution, and thickness. The Pooraka Formation and other colluvial and high-level alluvial deposits consist of gravel, sand, clayey sand, and clay; they also include residual material from weathered basement highs. Qfr is thus a composite morphotectonic unit rather than a stratigraphic formation, and consists of various lithologies of differing thicknesses,

mainly located around the margins of the Murray Basin. The Pooraka Formation itself is found as colluvial and alluvial material, on the western and northwestern margin of the Murray Basin in South Australia (Figs 122, 123). The alluvial material occupies stream channels incised through older materials of the flanks of the ranges, or overlying calcrete or older alluvials of the basin (Firman, 1973). The top of the Pooraka Formation is commonly a thin layer (up to 1–2 m) of sandy clay and clayey sand. Firman (1970a) called this the Callabonna Clay, and regarded it as marking the boundary between Upper Pleistocene and Holocene alluvial sequences.

The Pooraka Formation is not restricted to the Murray Basin: it is found flanking the slopes of the Mt. Lofty, Flinders, 'Olary', Peake and Denison, Everard, Musgrave and other ranges in southern Australia (Firman, 1970a). The Pooraka Formation is thus found in the Great Artesian, St. Vincent, Amadeus, and Officer Basins, as well as in the highland valleys of the above ranges (Firman, 1969a, 1970a; Thomson, 1969a).

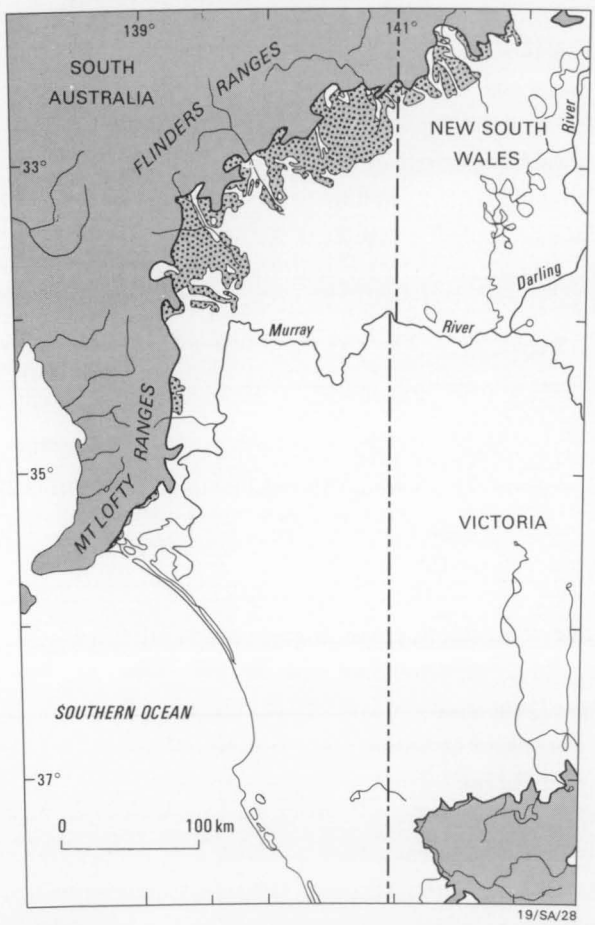


Fig. 122. Distribution of Pooraka Formation (South Australia) at western margins of Murray Basin. Extensive additional deposits of Pooraka Formation also occur within the adjacent Mount Lofty and Flinders Ranges.

Colluvial deposits similar to the Pooraka Formation are also found adjacent to the basin margins in New South Wales and Victoria. These consist of a variety of lithologies, including poorly sorted clayey sand, gravel, conglomerate, and breccia, with local calcrete intercalations and cappings. In addition to calcrete development, the unconsolidated clastic sediments may also be locally cemented by an iron or silica matrix. The colluvial deposits of the southeast Australian highlands do not have a common name, although the alluvium of the highland valleys is assigned to the Shepparton and Coonambidgal Formations. The local name Tawonga Gravels has been used for the piedmont deposits of the Kiewa River valley (Beavis, 1962; Lawrence, 1975).

Within the Murray Basin proper, residual and lag deposits of basement hills have been included in Qfr; rubble from Devonian sandstone outcrops, around the Darnick and Manfred Ranges, for example. Low-angle outwash fans associated with the Marmon Jabuk Scarp are also included in Qfr, although these are derived from Neogene sediments of the Murray Basin itself, and are composed mainly of fine-grained sand and silt.

The Pooraka Formation itself is between 1–5 m thick (Rogers, 1978); other Qfr deposits are of variable but comparable thickness. A low-angle Qfr alluvial fan adjacent to the Marmon Jabuk Scarp is up to 3 m thick (Rogers, 1980a); whereas in the Kiewa River valley of Victoria, piedmont deposits of the Tawonga Gravels are up to 30 m thick (Lawrence, 1975, his fig. 31).

Topography and vegetation. The Pooraka Formation and other Qfr deposits form low to high-angle alluvial and colluvial fans adjacent to basin margins and internal topographic highs. These are particularly extensive at the northwestern margin of the basin, where vegetation cover is sparse and restricted to grasses and low shrubs. Some scree slopes, particularly in northwestern areas, are almost unvegetated, whereas others are well grassed.

Palaeontology and age evidence. No palaeontological studies of Pooraka Formation, Tawonga Gravels, or Qfr in general have been published. The palaeoenvironment of these colluvial and alluvial units makes preservation of fauna unlikely, although some vegetal matter, particularly spores and pollen, is probably preserved locally. Age evidence is thus

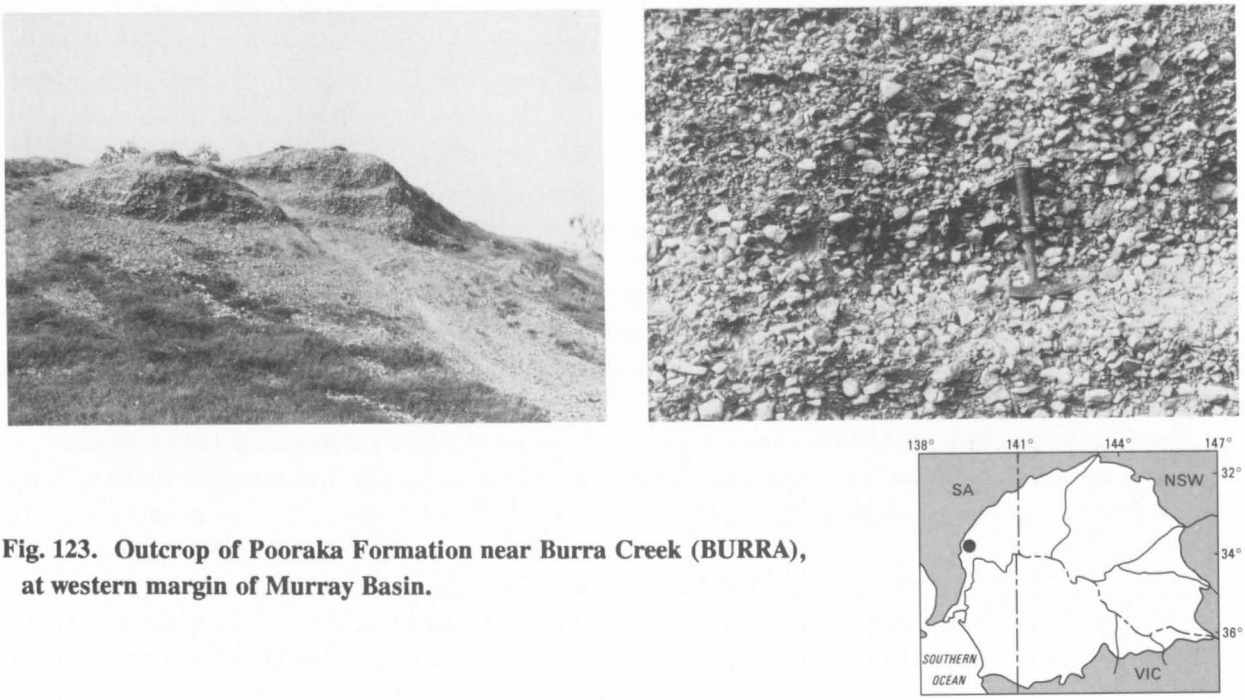


Fig. 123. Outcrop of Pooraka Formation near Burra Creek (BURRA), at western margin of Murray Basin.

entirely stratigraphic, and exact ages are unknown.

The Pooraka Formation overlies the Blanchetown Clay, and is therefore younger than about 0.6 Ma (Stephenson, 1986); it is also topped by the Callabonna Clay, which Firman (1973) regarded as marking the boundary between the Upper Pleistocene and Recent alluvial sequences in South Australia.

The Tawonga Gravels could be as old as Late Tertiary, as they overlie older alluvium (Renmark Group equivalents) and were eroded by the Kiewa River at the same time as that stream was depositing the Plio-Pleistocene Shepparton Formation. Other piedmont deposits of Victoria's highland valleys (Rowe, 1967; Newell, 1970) are probably of similar Plio-Quaternary age.

The Qfr fans adjacent to the Marmon Jabuk Scarp were allocated an Early Pleistocene age by Rogers (1980a). These overlie an unnamed dolomite (Qpu) which he regards (Rogers, pers. comm., 1984) as the oldest lagoonal deposit of the Murray Basin's coastal plain. Elsewhere in this Bulletin, an age of some 0.8 Ma to 0.9 Ma is tentatively assigned to Qpu, so these Qfr fans probably began to form shortly after that time. There are no stream channels cutting the fans today, and it is not possible to put an upper age upon their formation.

Elsewhere in the Murray Basin, scree slope, colluvial, and alluvial deposits may be as old as Eocene (many of Victoria's highland valleys contain Eocene sediments; see 'Ta'), whereas others may be much more recent, and/or active today.

Characteristics. Qfr is characterised by topographic expression, and to a lesser extent by geographic position and lithology. The coarser gravel and sand are easily recognised, but in places the transition from colluvial fan to basin sediment proper is not an abrupt change. This is particularly true of the transition between Pooraka Formation and Qdp, which is easily recognised on air photographs, but not necessarily at ground level. Other colluvial deposits, such as those at Burra Creek (Fig. 123) are quite obvious on the surface.

Environment of deposition. Qfr was deposited by fluvial (both alluvial and colluvial) processes adjacent to various uplands both within and at the margins of the Murray Basin. The most extensive fanglomerate deposits are those of the Pooraka Formation at the northwestern margin of the basin, which is thought to have been tectonically uplifted in the Plio-Pleistocene. Some of the high-angle scree slopes included within Qfr were also partly formed by gravitational accumulation of weathered and/or fragmented basement rocks. Piedmont deposits of highland valleys are also included within Qfr.

Stratigraphic nomenclature, type sections, and correlations. Qfr comprises many deposits which have not been formally named or described; the Pooraka Formation, Callabonna Clay, and Tawonga Gravels are exceptions to this, although these units are com-

posites of several lithologies.

The name 'Pooraka Clay' was used by Firman (1966b), and took its name from Pooraka railway station (ADELAIDE) in the St. Vincent Basin. Firman later (1969a) changed this to Pooraka Formation, and introduced the term Callabonna Clay (Firman, 1970a) for the uppermost member of Pooraka Formation. The Callabonna Clay takes its name from Lake Callabonna, in the Great Artesian Basin, and was described by Firman as the marker horizon characteristic of the Callabonna Soil (a pedogenic rather than geological unit). Neither Pooraka Formation nor Callabonna Clay have formal geological type sections, although Firman (1970a) did designate loosely defined type areas for the Callabonna Clay in the Great Artesian Basin, and Mt Lofty and Flinders Ranges areas.

The type area of the Tawonga Gravels is located outside the Murray Basin *sensu stricto*, in the Kiewa River valley (Beavis, 1962; Lawrence, 1975). Derivation of the name was not discussed by Beavis (1962), although he did mention a 'Tawonga Fault' in the same area. Lawrence (1975, p.58) extended the name Tawonga Gravels to cover a variety of lithologies in the highland valleys of Victoria as a whole.

Stratigraphic relationships. Qfr can overlie any older unit, including pre-Cainozoic basement at the margins of the basin, and Cainozoic sediments within it. Scree slopes of Qfr also overlies basement rises within the Murray Basin (e.g. Darnick and Manfred Ranges). Qfr associated with Cainozoic scarps within the Murray Basin can also overlie sediments of the basin itself: for example a Qfr apron adjacent to the Marmon Jabuk Scarp overlies lagoonal dolomites of Qpu.

In Victoria, the Tawonga Gravels and their equivalents overlie both Ordovician basement and Tertiary sediments (Beavis, 1962; Lawrence, 1975). In South Australia, the Pooraka Formation overlies Adelaidean sediments and Kanmantoo metamorphics of the Mt Lofty and Flinders Ranges, and Willyama Block basement on OLARY. In addition, the Pooraka Formation overlies Cainozoic basin sediments of the Morgan Limestone, Parilla Sand, Norwest Bend Formation, Blanchetown Clay, calcretes of the Bakara Soil, and possibly the Bungunnia Limestone. In the northwest, the Pooraka Formation grades basinward into unnamed sand plains (Qdp), which in turn locally grade into aeolian units, in particular the Woorinen Formation. Firman (1973) thought that the Woorinen Formation appeared to overlie the Pooraka Formation; whilst this relationship may occur locally, we regard the two units as being largely penecontemporaneous. Pooraka Formation is overlain by some modern alluvium (Qa), where intermittent streams flow into the basin from the ranges. In Victoria, the Tawonga Gravels are not overlain by any younger unit, but have been eroded in places by modern streams (cf. Lawrence, 1975, his fig. 31). Parts of the unit probably interfinger with, and overlie, the Shepparton Formation

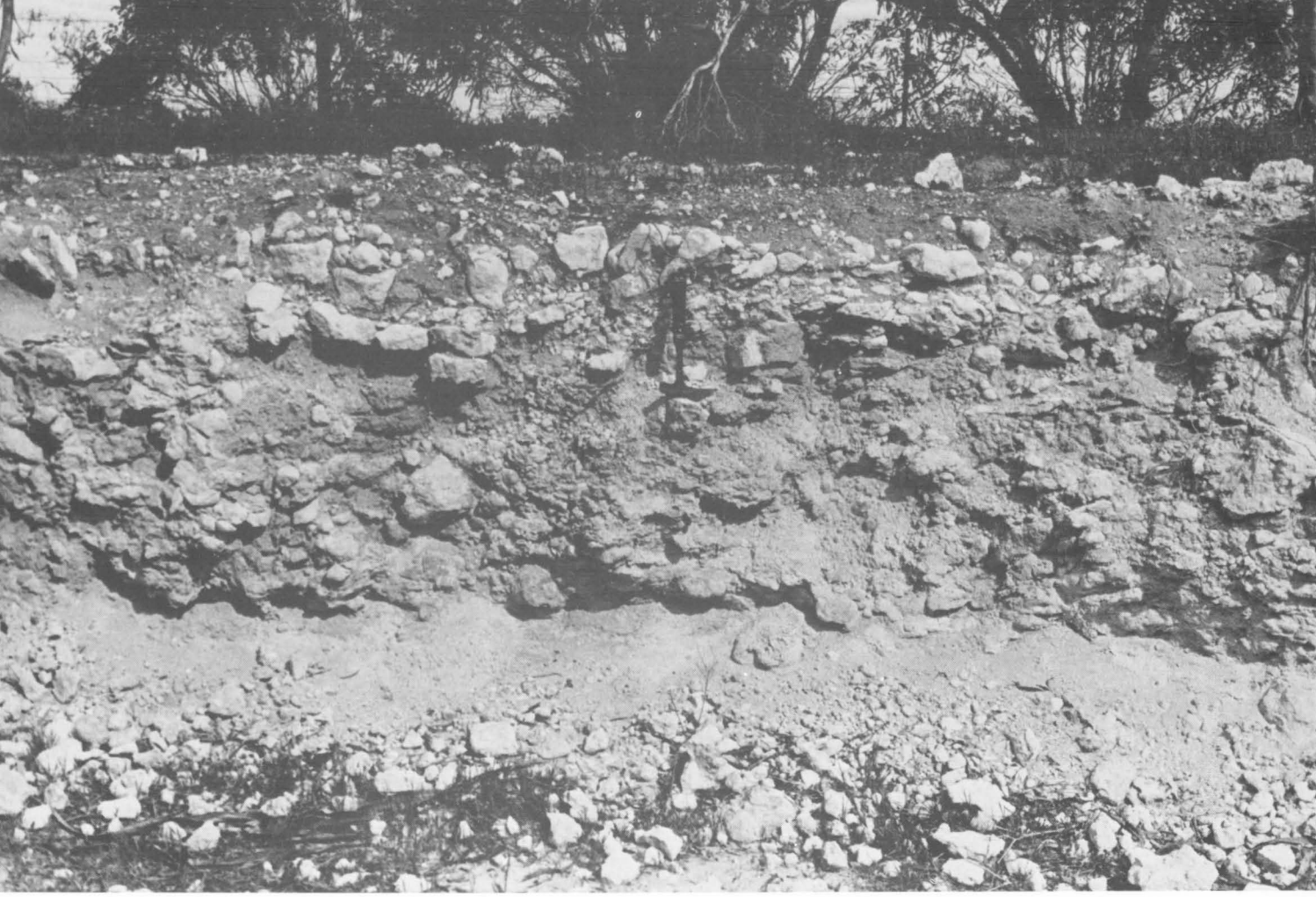
Remarks. Qfr is a composite unit chiefly composed of alluvial and colluvial sediments derived from the basin margins. In most cases, it ranges in age throughout the Quaternary, but historical usage of the name Pooraka Formation in South Australia has been slightly different from this. The 'Telford Gravel' was described by Firman (1967a) as an extensive fan unit flanking the Flinders, Mt Lofty, and 'Olary' Ranges. This is of Pleistocene age, and would normally have been included within Qfr. However, Telford Gravel has been cemented by calcrete of the Bakara Soil (Rogers, 1978), and is included in Qca on the enclosed geological map.

Data sources. Descriptions of Qfr deposits are provided in publications by Beavis (1962), Firman (1966b, 1967a, 1969a, 1970a, 1973), Rowe (1967), Thomson (1969a), Newell (1970), Lawrence (1975), Rogers (1978, 1980a), and Brown & Stephenson (1985, 1986).

Unit: Bakara Calcrete, Ripon Calcrete, Loveday Soil, and other unnamed calcrete deposits
Age: Quaternary, Early Pleistocene to Holocene, but mainly Late Pleistocene
Map symbol: Qca
Associated unit: Calcretes of the Woorinen Formation

Lithology. The calcretes of the Murray Basin range from strongly cemented pale-grey massive sheet calcrete (Fig. 124), through well-cemented calcrete rubble, to friable white and cream nodular and rhizolithic calcrete. Intraclasts of various lithologies set in the calcrete matrices are common, particularly within the sheet calcretes. Some of the more massive resistant calcretes also have a high silica content.

In South Australia, Firman (1963, 1966e, 1972, 1973) recognised several calcrete horizons of differing age, in particular the Ripon Calcrete, the Bakara Soil, and the Loveday Soil. Firman (1973) found that the pink Ripon Calcrete was older, harder, thicker, and more continuous than the off-white younger calcretes. The Ripon Calcrete often exhibits angular grey carbonate breccia, various intraclasts derived



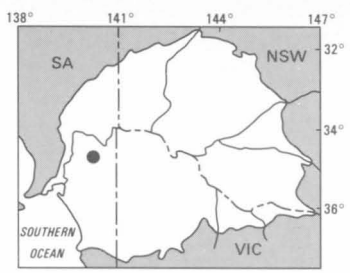


Fig. 124. Well-cemented calcrete rubble exposed beneath deflated dunes of Woorinen Formation, near Wambi (RENMARK).

from the parent sediments, and cemented carbonate concretions (Firman, 1973). The Bakara Soil was defined as a soil stratigraphic unit by Firman (1963), but has an indurated fossilised calcrete as its 'B' horizon (Firman, 1973). The youngest of the named calcretes is the Loveday Soil, which was also defined by Firman (1972) as a fossil soil horizon; it contains soft, nodular, and platy carbonate layers, and is the least well-indurated of the three units. However, calcretes within the Murray Basin are not limited to these three main units, and calcrete genesis has been an ongoing process throughout the Late Quaternary; calcareous rhizoliths are actively developing today in formations as young as the Holocene Semaphore Sand. In addition, several generations of pedogenic calcretes have been identified within the dunes of the Woorinen Formation, and have been used to define a number of component members within that formation (see 'Woorinen Formation' and Table 35).

Distribution, thickness, topography, and vegetation. Calcrete glaebules and rhizoliths occur in many soil profiles throughout the Murray Basin, and calcrete rubble underlies much of the aeolian landscape in the western half of the basin. In southwestern areas, calcrete locally forms massive resistant sheets, which in many places are the dominant geological feature at the surface (Fig. 125; see also enclosed 1:1 000 000 geological map). Farther to the east and north, pedogenic calcrete predominates. Thicknesses are highly variable, but the thickest calcrete profiles are no more than a few metres thick. The thickest probably represent several generations of stacked and coalesced profiles. Because calcrete can form within and on many different lithologies and landforms, the topographic expression of calcrete can take many forms, from massive, flat, resistant sheets,

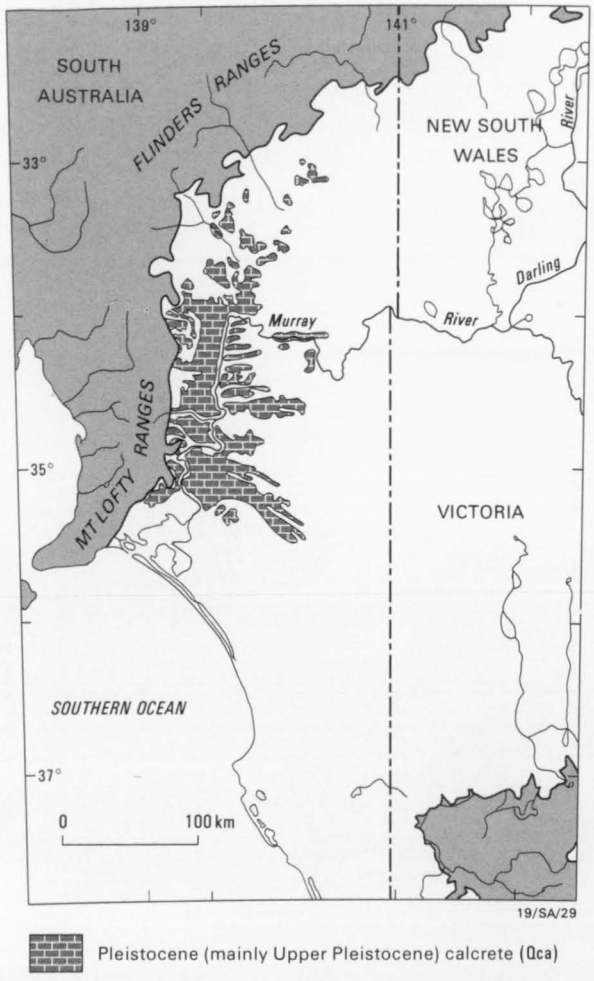


Fig. 125. Distribution of massive resistant sheets of calcrete, forming dominant mappable unit at surface of southwestern Murray Basin. Additional calcrete occurs within, and beneath, the aeolian sediment of the Mallee region of the western Murray Basin.

to subtle soil horizons within aeolian or coastal dunes. Similarly, the vegetation associated with calcrete horizons depends largely upon the underlying lithology and the local climatic regime.

Palaeontology. Calcretes do not normally contain fossils, although some potential for incorporating fossils reworked from the parent formation exists, particularly within sheet calcretes. Calcrete rhizoliths commonly preserve complex moulds of the tree or shrub root around which they were formed.

Age evidence. Calcretes can be of almost any age younger than the parent formation on or within which they were formed, and calcrete formation is usually a lengthy process. In South Australia, Firman (1973) attributed distinct ages to the Ripon Calcrete, Bakara Soil (and its calcrete), and the calcretes of the Loveday Soil, mainly on stratigraphic evidence (Fig. 126). These calcretes can to some degree be dated by the age of their parent formations. For example, the Ripon Calcrete overlies the Bungunnia Limestone (about 0.8 Ma old; Stephenson, 1986), the lower member of the Bridgewater Formation (more than 0.7 Ma old; Cook & others, 1977), and the unnamed Qpu dolomites (also at least 0.7 Ma old; see 'Qpu'). The Ripon Calcrete is not developed above the Woorinen Formation, the oldest parts of which are at least 0.4 Ma old, or on the upper member of the Bridgewater Formation, the oldest coastal ridges (probably 0.5 to 0.6 Ma old). On stratigraphic evidence the Ripon Calcrete thus appears to have first formed some 0.5 to 0.6 Ma ago. The Bakara Calcrete is less readily dated, but overlies the Ripon Calcrete, whilst underlying the Woorinen Formation (Firman, 1972, 1973; Rogers, 1978); this would suggest an age of some 0.4 to 0.5 Ma for the Bakara Calcrete. However, it is possible that both the Ripon and Bakara Calcrete were partly formed at the level of groundwater tables rather than at the then pedogenic surface, making stratigraphic dating of these units uncertain. The youngest of Firman's (1972, 1973) stratigraphically defined calcretes is the Loveday Soil, which overlies the Woorinen Formation, but underlies the Holocene deposits of the Molineaux Sand (Rogers, 1980a) and the Coonambidgal Formation (Rogers, 1978). The Loveday Soil is also absent from lunettes associated with the Upper Pleistocene to Holocene Yamba Formation. The calcrete of the Loveday Soil thus cannot be firmly dated, but formed sometime between 0.4 and 0.01 Ma ago, with an age nearer the upper limit being more probable. Essentially, most calcretes have developed during the past 0.5 Ma of arid to semi-arid climatic conditions.

Characteristics. Calcretes are characterised by lithology, petrology, and in some places by geomorphic expression. Units in the Murray Basin which appear superficially similar to the sheet-type calcrete (such as the Ripon Calcrete) include the areally restricted Pliocene Norwest Bend Formation and the Qpu dolomites; the former is distinguished from calcrete by its high fossil content, and the latter by its algal structures and lack of intraclasts. The Bungunnia Limestone is also superficially similar to some of the well-cemented sheet calcretes, but preserves algal structures and/or oolites, and is better-cemented than most of the rubbly pedogenic calcretes.

Environment of deposition. Calcretes are formed by carbonate precipitation in a number of environments. They can originate as part of the soil profile during pedogenesis, as did the Bakara Calcrete and the

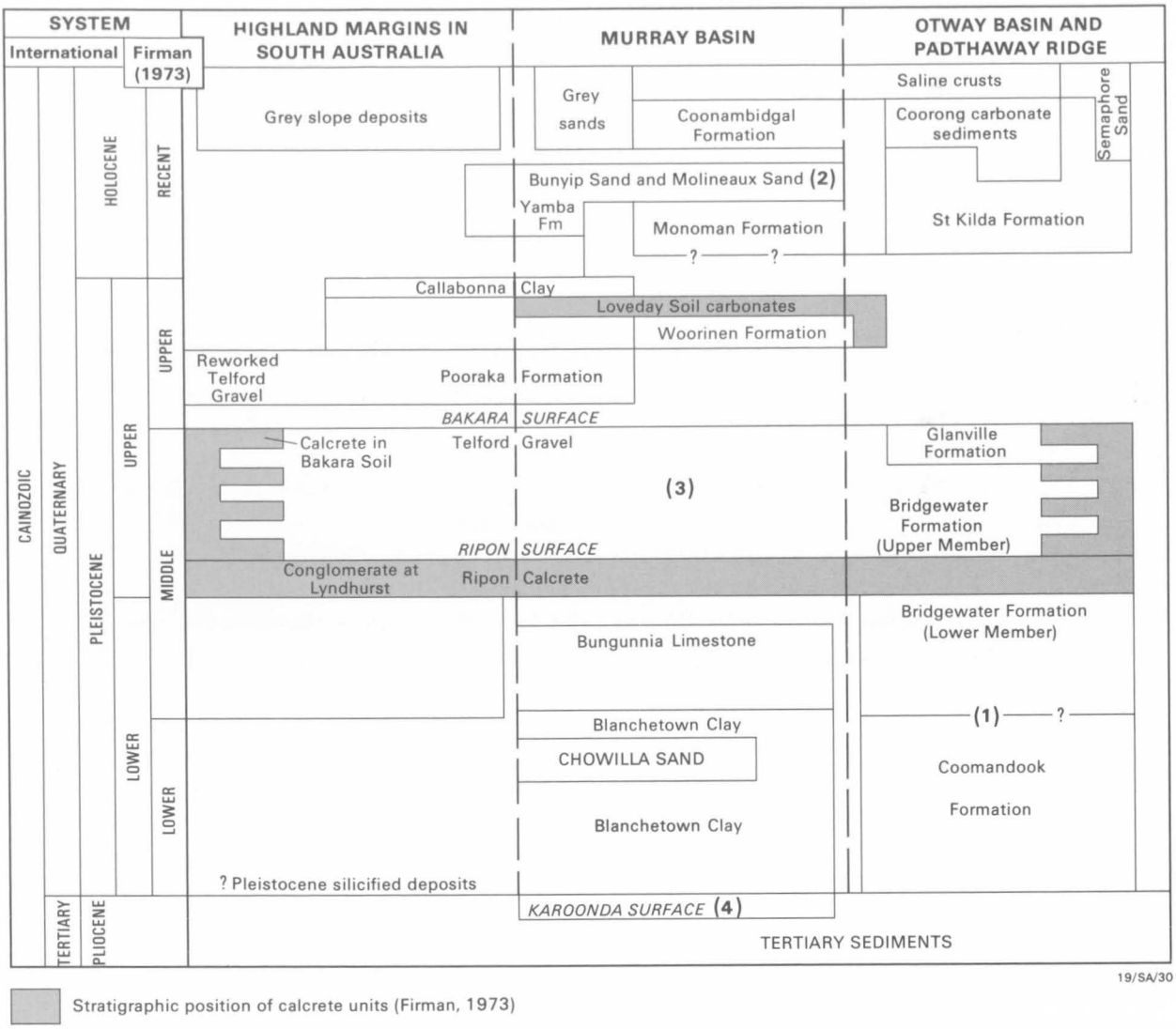


Fig. 126. Late Cainozoic stratigraphic table of Firman (1973) in South Australian part of Murray Basin; 'Padthaway Ridge' includes Buccleuch Embayment; Firman's three-fold subdivision of Pleistocene is not an internationally recognised subdivision; note that (1) the boundary between the base of the lower member of Pleistocene Bridgewater Formation and Pleistocene Coomandook Formation may be diachronous; (2) Bunyip Sand and Molineaux Sand with soft calcareous pipes appear to pre-date St. Kilda Formation; (3) Bakara Calcrete also occurs in western Murray Basin proper, as well as in Buccleuch Embayment (Rogers, 1980a); (4) Blanchetown Clay was first deposited in Late Pliocene (Stephenson, 1986), and overlies Karoonda Surface – dating the latter as no younger than Late Pliocene.

calcrete within the Loveday Soil. Calcretes can also develop by chemical interactions at the top of the groundwater table, within the parent soil or rock, as were some of the calcretes within the Bridgewater Formation. Rhizolithic calcretes are created by biogenic processes within the phreatic zone, which involve the chemical interaction of soil with plant roots; rubbly or nodular calcretes develop by gradual soil diagenesis in a chemically less-extreme environment than are the sheet calcretes. The calcretes has been the subject of a number of detailed studies, with emphasis on chemical interactions and diagenesis (Wetherby & Oades, 1975; Wetherby, 1980; Milnes & Hutton, 1983). Within the Woorinen Formation, calcrete layers are thought to have formed when climatic conditions were humid, dune systems were vegetated and inactive, and soil formation was accompanied by differentiation of a calcrete horizon (see 'Woorinen Formation' and Tables 30, and 35).

Stratigraphic nomenclature, type sections, and correlations. Only three of the calcretes within the Murray Basin have been named, all by Firman (1963, 1966e,

1967b) in South Australia. The Ripon Calcrete was named after the Hundred of Ripon on the west coast of Eyre Peninsula; the type section was designated as "Robinson Trench on the Ripon 1-mile map area and at Hall Bay" by Firman (1967b, p.6). As the location of the type section suggests, Firman (1967b) correlated the Ripon Calcrete of the Murray Basin with similar calcrete on Eyre Peninsula. The Bakara Soil was defined as a soil stratigraphic unit by Firman (1963) from Glanville, near Port Adelaide in the St. Vincent Basin. The Bakara Calcrete in the Murray Basin is the remnant 'B' horizon of this fossil soil, the 'A' horizon having been eroded away (Firman, 1966e). The Bakara Calcrete thus has no formal geological type section, and has been correlated as far as Millewa in Victoria (Firman, 1966e). The Loveday Soil was also defined as a soil stratigraphic unit, and was named after the Hundred of Loveday in County Alfred; it has no formal geological type section, and is widespread in South Australia, Victoria, and New South Wales (Firman, 1966e). In addition to the above, several illuvial calcareous soil ghorizons have been named within the Woorinen Formation (Table 35), and the 'Widgelli Pedoderm' identified within the near-surface Shepparton Formation.

Stratigraphic relationships. Calcrete in one form or another is associated with almost every Quaternary unit in the Murray Basin, with the exception of modern lacustrine sediments (Ql), the Coonambidgal Formation and other modern stream deposits, and the active aeolian dunes of the Bunyip Sand. Calcrete is also largely absent from the Molineaux–Lowan Sands and from the youngest member (Piangil) of the Woorinen Formation, although calcareous rhizoliths are locally present. Calcrete is particularly well developed within the Woorinen Formation (Table 35).

Rogers (1980a) records the Bakara Calcrete resting directly upon the Ripon Calcrete in parts of the Pinnaroo Block. In the Otway Basin, the modern coastal dunes of the Semaphore Sand locally overlie Bakara Calcrete developed at the top of the Bridgewater Formation (Firman, 1973), but such a relationship has not been recorded in the Murray Basin.

Hydrogeology and economic geology. Many calcretes of the Murray Basin were formed by chemical processes associated with groundwater, but they do not generally form aquifers and some massive, resistant sheet calcretes form local aquitards beneath dune sands of the Woorinen Formation. The more robust calcretes (such as the Ripon Calcrete and the Bakara Calcrete) have been used as coarse road aggregate (Firman, 1972; Rogers, 1978, 1980a).

Remarks. Calcretes are common throughout the western Murray Basin, and were formed as the climate of the area became semi-arid following the demise of Plio-Pleistocene Lake Bungunnia at about 0.6 Ma ago (An Zhi–Sheng & others, 1986).

Data sources. Descriptions of calcretes are presented in publications by Firman (1963, 1966e, 1967b, 1972, 1973), Wetherby & Oades (1975), Cook & others (1977), Rogers (1978, 1980a), Wetherby (1980), Milnes & Hutton (1983), and Milnes & Ludbrook (1986).

Unit: Unnamed Pleistocene marginal-marine and lagoonal unit
Age: Early to ?Late Pleistocene
Map symbol: Qpu
Informal nomenclature: 'Bungunnia Limestone equivalents'.

Lithology. The unnamed unit Qpu is a pale-grey, fine-grained, and well-cemented dolomite, with abundant algal material; it is best-described as a dolomitic algal boundstone. It contains intraclasts of sandstone, calcarenite, and dolomite, and is locally capped by sheet calcretes.

Distribution and thickness. Qpu has a very limited distribution, being restricted to the northern part of the Buccleuch Embayment (Fig. 55) in the western Murray Basin; more specifically, Qpu occupies the flat plain between the erosional Marmon Jabuk Scarp and the Cooke Plains Embayment (an extension of Lake Alexandrina) on PINNAROO (Figs 127, 128).

The thickness of Qpu varies considerably: Rogers (1980a) regarded thicknesses in excess of 3 m as typical, though the thickness of Qpu ranges between 1 and 27 m, with most boreholes encountering 4–15 m (Brown & Stephenson, 1986).

Geometry, structure, topography, and vegetation. The upper surface of Qpu forms a flat sheet-like deposit near or at the surface of a flat plain, and is normally covered only by a thin soil or by a calcrete layer. The lower surface of Qpu is more uneven, and variations in the thickness of the unit reflect the underlying topography at the time of deposition. Like some of the freshwater limestone of the Padthaway Formation, Qpu is characterised by blocky fracturing and deformed bedding. Rogers (1980a) suggested that the latter may have been caused by fluid expulsion during diagenesis. Thus, although individual blocks of Qpu are well indurated, outcrops upon the plain

have a rubbly appearance, which is further enhanced by the local development of Ripon Calcrete upon the upper surface of the Qpu dolomite.

The Qpu plain shows little relief, and is only some 20 m above current sea-level; the Molineaux Sand forms low dunes on the plain in a few localities. Some of the plain is under wheat cultivation, but the natural vegetation consists of low trees (less than 10 m high), low shrubs, and grasses (including 'blackboy' grass trees).

Palaeontology and age evidence. There has been no systematic palaeontological study undertaken on the Qpu dolomite. An abundance of algal structures is seen in outcrops and handspecimens as well as in thin sections. In most locations, Qpu appears to be an algal boundstone rather than a chemically precipitated dolomite.

The age control on the unnamed Qpu dolomite is stratigraphic, and partly circumstantial. Rogers (1980a) correlated Qpu with the Bungunnia Limestone, which is associated with Plio-Pleistocene Lake Bungunnia (Firman, 1965a); however, although the two units have similar lithologies and may be partly time equivalent, they are genetically unrelated (Stephenson, 1986). P.A. Rogers has since advised (pers. comm., 1984) that he regards Qpu as representing the oldest lagoonal sediments of the modern coastal plain, similar to but predating the lagoonal deposits of the Padthaway Formation.

The Marmon Jabuk Scarp (Fig. 127), which bounds Qpu to the north and east, is an erosional feature caused by an Early Pleistocene marine incursion into the western Murray Basin; this short-lived transgression also heavily eroded the Miocene limestone in this part of the basin, and led to the deposition of the Coomandook Formation. The interfingering between the Qpu dolomite and the Qfr colluvial fans adjacent to the Marmon Jabuk Scarp (as shown by Rogers, 1980a) indicates that there was a hiatus between the deposition of the Coomandook Formation and that of the unnamed Qpu dolomite. The event which led to the deposition of the later unit must therefore have been a separate, minor marine transgression.

If Rogers (1980a) is correct in relating Qpu to the Bridgewater Formation, the former unit will be of approximately the same age as the second oldest Bridgewater Formation strandline, in the area between the towns of Coomandook and Ki Ki (Figs 127, 128); the oldest strandline abuts the Pliocene sand of the Pinnaroo Block, and would predate the deposition of Qpu. Correlation of the dune sequence in the Coomandook–Ki Ki area with those farther south is not certain, but it is likely that this strandline and that immediately east of Keith (NARACOORTE) were formed during the same highstand of sea-level (Rochow, 1969; Rogers, 1980a, 1980b). The latter strandline can be shown to be no younger than the East Naracoorte Range, which is at least 0.69 Ma old (Cook & others, 1977); this means that the unnamed Qpu dolomite is also at least some 0.7 Ma old. The presence of the Ripon Calcrete developed at the top of Qpu adds some weight to this argument, as this calcrete is shown elsewhere in this Bulletin to be approximately 0.5 to 0.6 Ma old.

Putting a maximum possible age on Qpu presents some difficulties. Qpu overlies the sandy, reworked calcarenite of the Coomandook Formation, which is thought to have been deposited during the Early Pleistocene (see 'Coomandook Formation'), but is itself of debatable age. As noted previously, deposition of Qpu was probably related to a rise in relative sea-level, and on this basis is tentatively assigned an age of 0.8 to 0.9 Ma.

Characteristics. Qpu is primarily characterised by its lithology, geographic location, and stratigraphic position. Qpu's well-indurated nature distinguishes it from the underlying, sandy, partly consolidated calcarenite of the Coomandook Formation. Qpu can be distinguished from the Oligo-Miocene limestone of the Murray Group by lithology, stratigraphic position, and the distinctive fossil content of the older units.

Environment of deposition. Rogers (1980a) described the unnamed Qpu dolomite as having an environment of deposition ranging from freshwater lacustrine to saline-water lagoonal; however, he now regards the unit as comprising entirely coastal lagoonal carbonate, rather than lacustrine sediment, and considers Qpu to be facies-equivalent to the younger Padthaway Formation (P.A. Rogers, pers. commun., 1984). This view may be an over-simplification. The Padthaway Formation occupies narrow, inter-ridge corridors between the stranded coastal beach–dune complexes of the Bridgewater Formation, and contains a variety of sediments, including freshwater limestone, swampy mud and peat, and some fluvial and aeolian material. On the other hand, Qpu occupies a much larger plain, partly between the two oldest Bridgewater Formation dunes in the area, but also partly between the erosional Marmon Jabuk Scarp and the modern estuary of the Murray River. In addition, Qpu is lithologically much more homogeneous than is the Padthaway Formation. These factors suggest that Qpu was deposited in a somewhat different environment from that of the

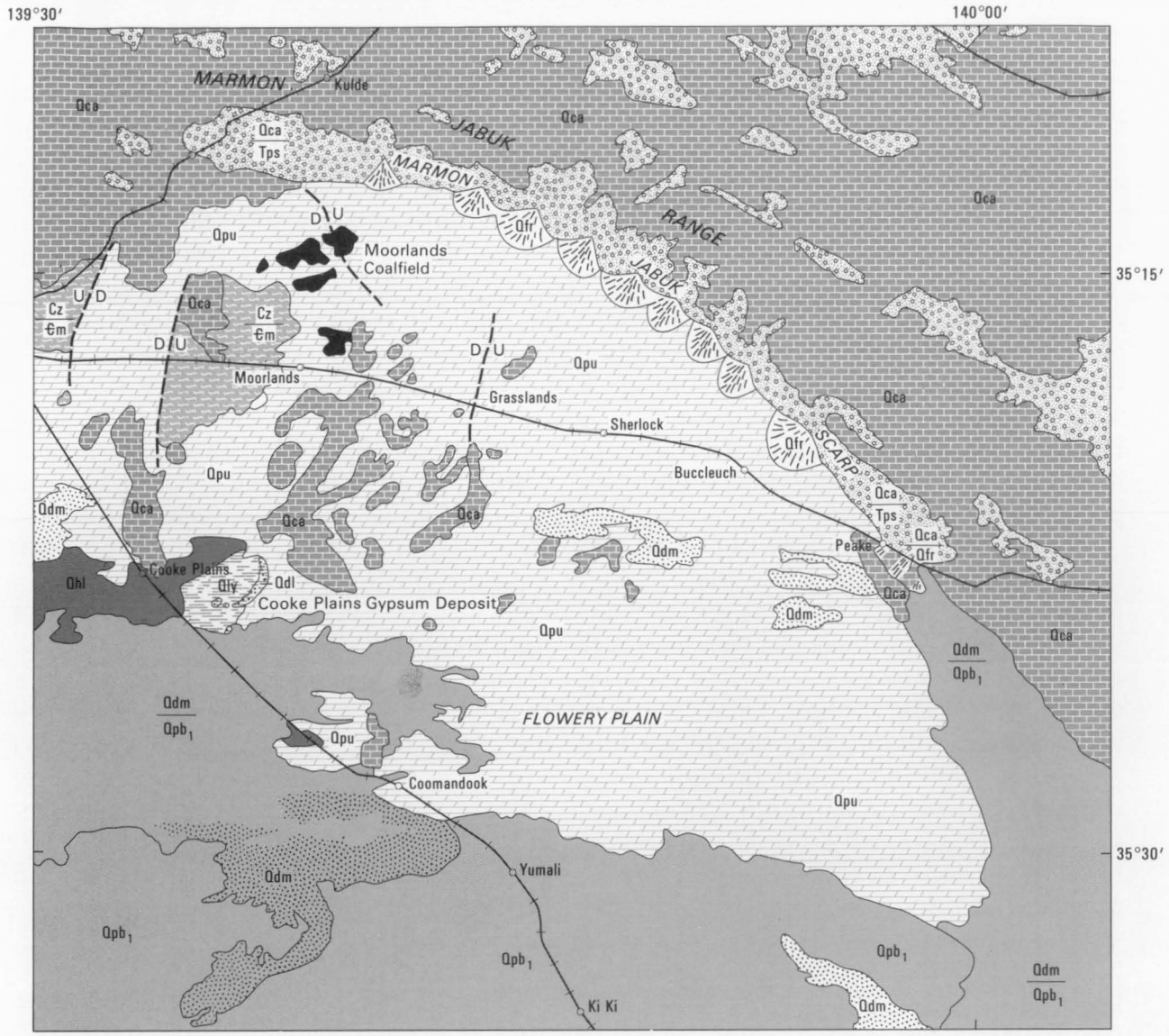


Fig. 127. Distribution of unnamed Pleistocene marginal-marine and lagoonal unit 'Qpu' on PINNAROO (after Rogers, 1980a).

Padthaway Formation, which was deposited in restricted Coorong-type lagoons and inter-ridge fluvio-lacustrine environments. Qpu may have been deposited in a marginal-marine, carbonate-rich lagoon, which was more open to the sea. Even so, the preponderance of algal material suggests a relatively low-energy environment, such as a protected carbonate shelf. The Qpu lagoon was probably partly protected, because Kanmantoo metamorphic basement is at very shallow depths near the western end of the lagoon (Fig. 127). Unlike the Padthaway Formation, swampy and fluvio-lacustrine sediments did not accumulate on top of the Qpu dolomite, but calcrete is locally very well developed, which suggests that the absence of clastics is due to non-deposition rather than the erosion of post-Qpu sediments.

It is likely that the Marmon Jabuk Scarp, which forms the northern and eastern boundaries to Qpu (Fig. 127), is the product of two separate erosional events, accompanying two separate marine transgressions. The first caused most of the erosion at the edge of the Pinnaroo Block, resulting in reworking of the Murray Group limestones over a wide area of the Buccleuch Embayment (Fig. 55), and deposition of the Coomandook Formation. The second event occurred later in the Pleistocene, was of far more restricted extent, and resulted in erosion of the Loxton–Parilla Sands, and deposition of Qpu.

In summary, Qpu was deposited during a minor Pleistocene marine incursion into the western Murray Basin. This transgression marked the beginning of the deposition of the series of coastal ridges and lagoonal sediments, which dominates the Quaternary of coastal southeastern South Australia and parts of western Victoria. Unlike areas farther south, the Qpu embayment does not show evidence of post-depositional uplift.

Stratigraphic nomenclature and type section. Rogers (1980a) noted that Qpu is lithologically and stratigraphically distinct from the Padthaway Formation, to which it is genetically related, and is a geological unit in its own right. Qpu is not a formally defined geological unit and requires a formal name, definition, and type section. As discussed previously, Rogers (1980a) used the term 'Bungunnia Limestone equivalents' to describe the unit. Earlier, Firman (1973) had mapped the entire area covered by Qpu as calcrete. We take the type area of Qpu to be as shown on PINNAROO, between the Marmon Jabuk Scarp and the Cooke Plains Embayment (Fig. 127).

Stratigraphic relationships. Qpu disconformably overlies the Lower Pleistocene marine Coomandook Formation. At the southern end of its occurrence (near the town of Coomandook, Fig. 127), Qpu interfingers with the lower member of the Bridgewater Formation.

Rogers (1980a) regarded Qpu as analogous to the interdune, back-barrier sediments of the Padthaway Formation, in that the Qpu dolomite is located between the Marmon Jabuk Scarp and the oldest Bridgewater Formation beach–dune complex in this area. However, Qpu does not have any direct stratigraphic relationship with the younger and more coastward Padthaway Formation as the two units are currently defined.

At its northeastern extremities, Qpu abuts the Marmon Jabuk Scarp (Fig. 127), and partly interfingers with, and is overlain by, sand and gravel (Qfr) of low-angle alluvial fans adjacent to the escarpment (Rogers, 1980a). The escarpment itself is not an impressive topographic feature, having a maximum relief only some 50 m above the Qpu plain, and the colluvial outwash deposits do not impinge far onto the plain: the maximum radius length of the Qfr fans is less than two kilometres.

The Ripon Calcrete is commonly developed on the upper parts of the Qpu dolomite (Rogers, 1980a). Qpu is also disconformably overlain by the aeolian Molineaux Sand, and by lacustrine deposits of the Cooke Plains Embayment, which impinge on to the western margin of the Qpu plain (Fig. 127). These latter sediments comprise muds of the St. Kilda Formation (Qho), a gypsiferous lake of the Yamba Formation (Qly), and an associated gypsiferous lunette (Qdl).

Correlations. Two recurrent themes throughout this Bulletin are the problems involved in accurately dating many of the Pleistocene units within the Murray Basin, and correlating units with poor age control, such as Qpu, with other formations. The preponderance of algal material in the Qpu dolomite makes this unit superficially similar to the Bungunnia Limestone, but the two formations cannot be correlated directly, as they are genetically unrelated and only partly time equivalent. Qpu is the product of a saline coastal lagoon, whereas the Bungunnia Limestone is the product of a large land-locked freshwater lake. Rogers' (1980a) correlation of Qpu as time-equivalent to the Bungunnia Limestone may, however, be partly correct. Stephenson (1986) showed that the Bungunnia Limestone was deposited late in Lake Bungunnia's history, and may have been deposited sometime between 1.2 and 0.7 Ma ago. Qpu is here regarded as a partial time and facies equivalent of the lower member of the Bridgewater Formation; Qpu is also partly time-equivalent to the

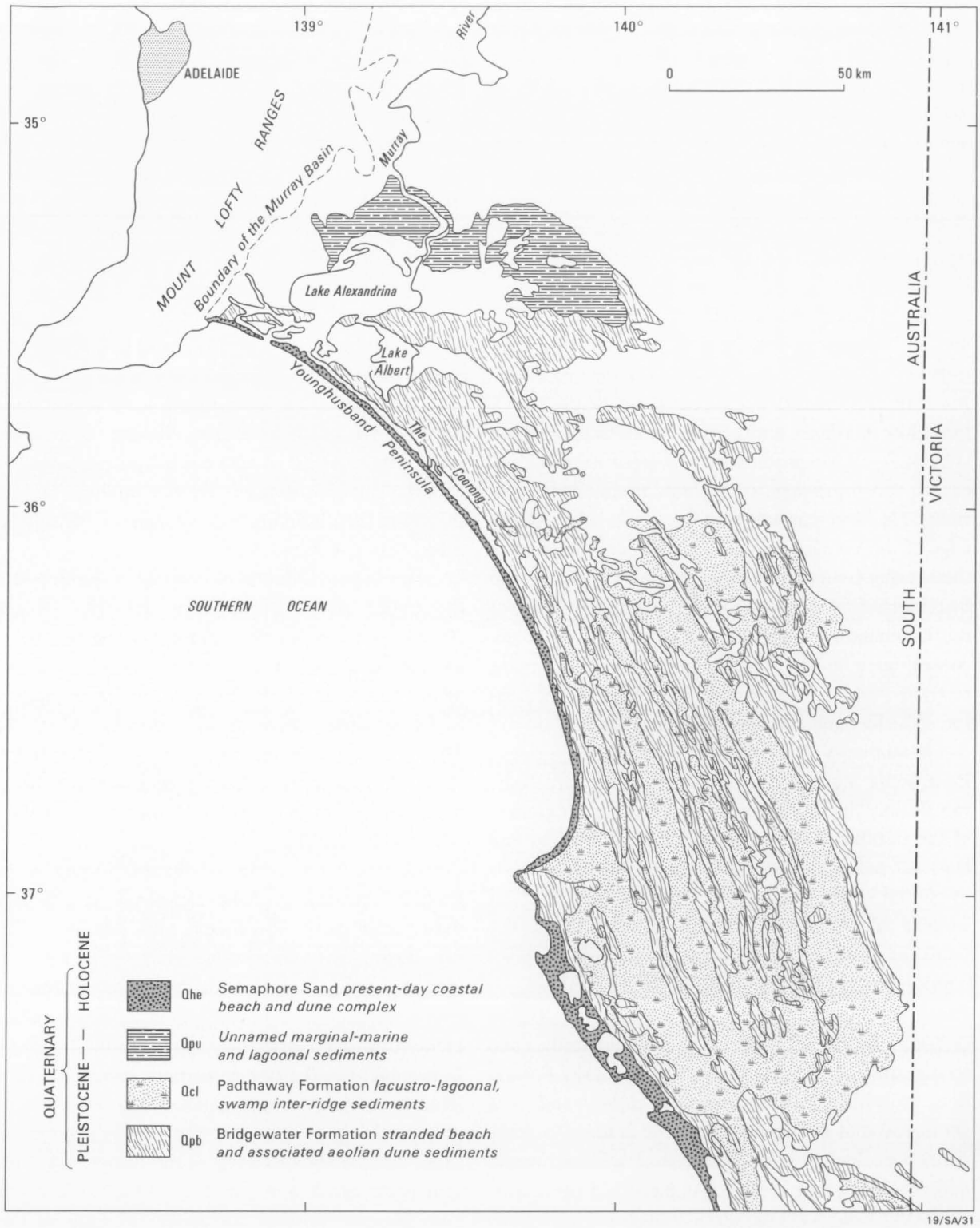
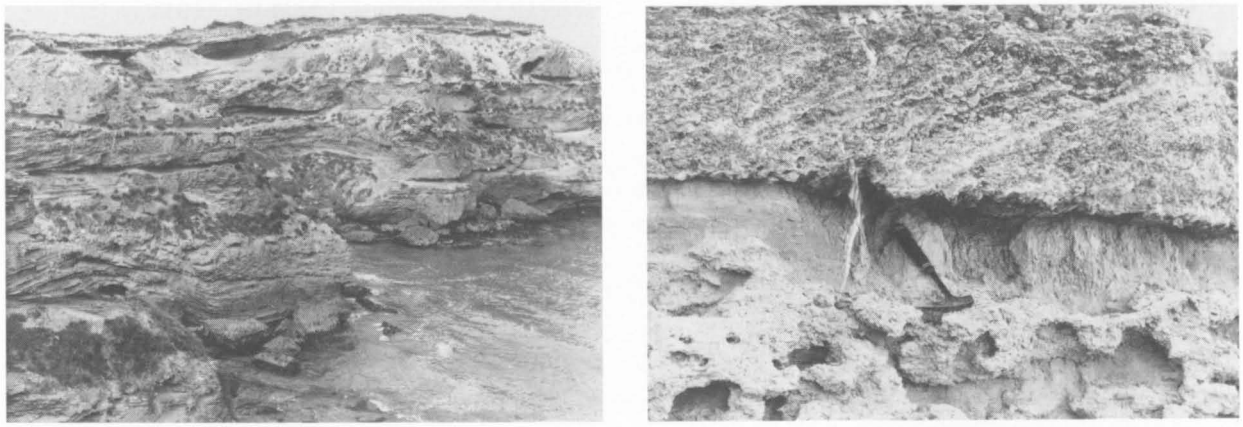


Fig. 128. Distribution of stranded coastal ridges of Bridgewater Formation (Qpb), and inter-ridge sediments of Padthaway Formation (Qcl); also distribution of unnamed lagoonal sediments of Qpu, and present-day coastal beach and dune complex of Semaphore Sand (Qhe), in southeast South Australia.



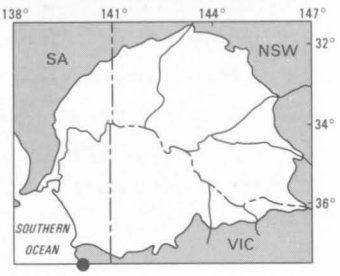


Fig. 129. Calcarenite of Bridgewater Formation, exposed by coastal erosion 30 km southwest of Mount Gambier.

Blanchetown Clay, the Shepparton Formation, and the Pooraka Formation and other colluvial deposits (Qfr). Each of these units was deposited over a considerably longer time interval than was Qpu.

Hydrogeology. Qpu is a fractured, well-indurated surface and near-surface unit which neither holds, nor hinders the movement of, groundwater.

Data sources. Little information is available on Qpu; references to the unit are in Firman (1965b), and Rogers (1980a, 1980b).

Unit: Bridgewater Formation
Age: Early to Late Pleistocene
Map symbol: Qpb
Synonyms: Bridgewater Limestone, Bridgewater Formation dune limestone
Informal nomenclature: 'Bridgewater Bay sands', 'Bridgewater Bay dunestone'

Lithology. The Bridgewater Formation (Fig. 129) is composed of poorly consolidated, pale-yellow or pinkish brown, fine to coarse-grained calcareous sand or calcarenite. It consists of an average of 50% carbonate and 50% quartz sand, but the carbonate ranges between 10% and 100% (Cook & others, 1977). The older Bridgewater Formation forms beach ridges, which have a significantly lower carbonate content than do younger ridges closer to the modern coast. Cook & others (1977) thought that this may be due to either the contribution of quartz sand eroded from the Pliocene sands to the east (the Loxton–Parilla Sands), or due to the increasing age of beach ridges to the east.

The Bridgewater Formation calcarenites are composed of fine to very coarse, rounded and fragmentary skeletal carbonate grains, together with fine to medium, moderately rounded to well-rounded detrital grains. The detrital grains are predominantly quartz, with minor feldspar and trace amounts of heavy minerals. Intraclasts derived from older indurated limestones (mainly the Gambier Limestone and the Coomandook Formation) locally contribute to the carbonate component of the Bridgewater Formation. Sparry calcite forms the cement in most of the sands (Cook & others, 1977).

Calcretes are locally present within the Bridgewater Formation (Firman, 1973), as are palaeosols in some of the composite beach dunes, and on the West Naracoorte Range (Cook & others, 1977).

Distribution and thickness. The Bridgewater Formation in the Murray Basin is located between the Pinnaroo Block and the present coast (Fig. 128), overlying the southern part of the Buccleuch Embayment (Fig. 55), and extending south to overlie the Gambier Embayment of the Otway Basin (Fig. 64). This area is colloquially known as the Gambier Sunklands (O'Driscoll, 1960), and consists of a series of stranded coastal beach and dune ridges, separated by interdune swampy flats, shallow lagoons, lakes, and fluvial sediments. The Bridgewater Formation is made up primarily of these stranded coastal ridges,

but also includes eroded coastal and littoral calcarenite remnants underlying some interdune corridors. The inter-Bridgewater ridge lagoonal and fluvial sediments are described under 'Padthaway Formation'. The Bridgewater Formation is found as far north as the town of Coomandook, and as far south as Cape Bridgewater in the Victorian part of the Otway Basin; it has a very patchy distribution, with at least seventeen major ridges in the Murray Basin, and numerous minor occurrences (Rochow, 1969). The Bridgewater Formation has also been found to underlie the modern beach–barrier and dune complex of the Younghusband Peninsula (see 'Semaphore Sand'), and the Coorong lagoon (Firman, 1973); it is also known to occur offshore in the Otway Basin off western Victoria (Boutakoff, 1963), although the distribution and number of these drowned Bridgewater Formation ridges are poorly defined (Kenley, 1971, 1976b, 1988b). Other Bridgewater Formation deposits form a mantle over topographic rises (see below).

The thickness of the Bridgewater Formation is very variable, as would be expected from its environment of deposition. Cook & others (1977) recorded a maximum thickness in excess of 80 m in the West Naracoorte Range, whilst thicknesses of the Bridgewater Formation found in boreholes range from 70 m down to 2 m, with the most common thicknesses being 15–40 m (Brown & Stephenson, 1986). Rogers (1980a) suggested that the Bridgewater Formation had an average thickness of 15 m, but this was in its most northerly area of occurrence, on PINNAROO.

Geometry, topography, and vegetation. The Bridgewater Formation forms a series of stranded coastal ridges subparallel to the modern coast, and extending up to 90 km inland (see Fig. 92). Most Bridgewater Formation ridges do not exceed 50 m in elevation above the surrounding interdune plains, and a topographic expression of some 15–20 m is more typical of the smaller ridges. The ridges take the form of stabilized low-angle dunes, and are vegetated by low trees (less than 10 m tall), low shrubs, and tussock grasses.

In addition to the dune ridges, and the offshore dune remnants mentioned above, other aeolianites referred to the Bridgewater Formation include deposits on other hills and elevations (Firman, 1973). These deposits occur on nearly every volcanic hill on PENOLA, and Hossfeld (1950) recorded that they may be found at elevations of more than 200 m above sea-level.

Palaeontology. The Bridgewater Formation has an abundant shelly fauna, which has yet to be thoroughly described, although some work has been done on material from isolated localities. Tindale (1933) found individuals and species of the bivalve genus *Chione* dominant amongst the shelly fauna of the Woakwine Terrace, south of Kingston, SE; whilst Sprigg (1952a) described the fauna of bores from Robe Harbour.

Age evidence. Most of the abundant fossils are strongly abraded and none are known to be biostratigraphically diagnostic (Cook & others, 1977). Early workers had varied opinions on the age of the Bridgewater Formation. Crocker & Cotton (1946) considered that the dune sequence was deposited in the Early Pleistocene, whereas Hossfeld (1950) thought a Late Pleistocene age to be more likely. Sprigg (1952a) was also of the latter opinion, and attempted to correlate the distribution of dune ridges with the sea-level curves of Milankovitch and Zeuner, reaching the conclusion that the sequence to the west of the West Naracoorte Range was not older than 0.54 Ma.

Boutakoff (1963) studied the Bridgewater Formation in the Otway Basin of western Victoria, and considered it to have been deposited throughout most of Quaternary time. He found two distinct sets of calcarenites within the Bridgewater Formation near Portland: the younger he thought to be of Late Pleistocene age, while the older had been partially levelled to an abrasion platform. Boutakoff (1963) related this abrasion platform to the 'middle Pleistocene' Mindel–Riss Interglacial high sea-level, and hence regarded the lower dune set as being of Early Pleistocene age.

In South Australia, Firman (1967a) also subdivided the Bridgewater Formation into an upper and a lower member. These members are locally separated by a thick zone of soil and clastic carbonate deposits, known as the Ripon Calcrete (Firman, 1967b). The Ripon Calcrete is the oldest distinct calcrete horizon in the South Australian part of the Murray Basin (Firman, 1973), and postdates the Blanchetown Clay where those two units occur together (Rogers, 1980a). The youngest age of the upper Blanchetown Clay is of the order of 0.6 Ma (An Zhi–Sheng & others, 1986), making it likely that the Ripon Calcrete, above the lower member of the Bridgewater Formation, is less than 0.6 Ma old. Conversely, the upper member of the Bridgewater Formation can be assigned an age no younger than 0.4 Ma, as the Ripon Calcrete predates the aeolian Woorinen Formation where the two units occur together (Firman, 1972), and the younger unit is up

to 0.4 Ma old (see 'Woorinen Formation'). On stratigraphic evidence, the break between the upper and lower members of the Bridgewater Formation can be placed at between some 0.4 and 0.6 Ma ago.

Magnetostratigraphic dating has been applied to the Bridgewater Formation by Cook & others (1977) and Idnurm & Cook (1980), who showed that all the calcarenite dunes in the Buccleuch Embayment and in the South Australian part of the Gambier Embayment are normally polarized, with the exception of the most easterly strandline, the East Naracoorte Range, which showed reversed polarization. This implies that the East Naracoorte Range formed during the Matuyama Reversed Polarity Epoch and is therefore more than 0.69 Ma old, whereas all the younger dunes to the west formed during the Brunhes Normal Polarity Epoch, and are therefore less than 0.69 Ma old (Cook & others, 1977).

Rogers (1980a) assigned both the East Naracoorte Range and the West Naracoorte Range to the lower member of the Bridgewater Formation, and all dune ridges farther west to the upper member. The West Naracoorte Range is a composite dune composed of four superimposed strandlines, and splits into four separate ranges north of Naracoorte (Rochow, 1969; Cook & others, 1977). This is consistent with the time-range of 0.4 to 0.6 Ma outlined above for the break between the two members of the Bridgewater Formation, with perhaps a slight leaning towards the older end of the time range.

Characteristics. The Bridgewater Formation is primarily characterized by its geomorphic expression as stranded coastal ridges, and its geographic position on the coastal plain of southeastern South Australia and western Victoria. However, the Bridgewater Formation is not restricted to dune ridges. Boutakoff (1963) described "submerged dunestone ridges ...eminently characteristic of all dunes in the Bridgewater Formation" near Portland, Victoria, and also noted that "such dunes have been formed far out over the continental shelf and, although their shapes have no doubt been subdued by marine planation, their roots are still present in the sea bottom over a wide sub-coastal belt" (Boutakoff, 1963, his p.56). In addition, Firman (1973) recorded Bridgewater Formation underlying the modern beach ridge and lagoon complex of the Semaphore Sand and the Coorong, and also forming the modern sea bed in that area. In these circumstances, lithology is an important secondary characteristic for recognition of the Bridgewater Formation. This is also the case for the Bridgewater Formation deposits, which mantle topographic rises in the Gambier Embayment.

The Bridgewater Formation is lithologically distinct from most geologic units within its geographic area. In many places, it is overlain by the Molineaux Sand, which, unlike the Bridgewater Formation, does not contain detrital carbonate reworked from older formations, lacks calcrete, and has a very quartz-rich composition, and highly mobile habit. The Bridgewater Formation could be confused with the Pliocene Loxton–Parilla Sands in the few locations where the two units are adjacent, but the Pliocene sands are quartz-dominated, and have a more reddish or red-brown colour than most of the Bridgewater Formation calcarenites; the two units are easily distinguished in borehole logs.

The Bridgewater Formation is difficult to distinguish from the Coomandook Formation, as these units have a similar lithology, and each has abundant abraded fossils; as the Coomandook Formation crops out in only one possible location, separating the two units is only a problem in borehole logs.

Environment of deposition. The Bridgewater Formation is a composite geological unit and accumulated in a wide range of coastal environments; ranging from lower shoreface through beaches, to beach dunes and coastal-derived aeolian dunes. In addition, these features have usually been modified by marine processes and/or surface erosion, which together with the diversity of environments of deposition led to a wide range of sedimentological features. Cross-bedding is particularly common in outcrops and cores. A notable feature of this cross-bedding is that it is more gently dipping at the base of the Bridgewater Formation sequence (Cook & others, 1977); when considered in conjunction with the downward increase of shelf-derived material within ridges, those authors took this to suggest that the lower parts were deposited in beach or near-beach environments, whereas the upper parts accumulated under aeolian conditions.

Some of the dune ridges are composite features, with palaeosols developed at various levels (Cook & others, 1977), reflecting several periods of aeolian accretion. As mentioned previously, the Bridgewater Formation also includes aeolianites which do not form dunes, but which mantle topographic rises (Hossfeld, 1950); the formation also embraces drowned dunes below present sea level, these latter features having been heavily modified by marine processes (Sprigg, 1952b; Boutakoff, 1963).

The Bridgewater Formation forms a distinctive series of sub-parallel stranded coastal ridges in the

Murray Basin and the Gambier Embayment of the Otway Basin. Cook & others (1977) suggested that the unit might not be the regular regressive sequence assumed by earlier workers, such as Sprigg (1952a,b), and noted that a number of dunes appear to be composite features, reflecting more than one sea-level change. Cook & others (1977) were of the opinion that there had been at least twenty high stands of sea-level since 0.69 Ma. The presence of submerged ridges in the Portland area of the Otway Basin (Boutakoff, 1963), and of Bridgewater Formation sediment offshore in South Australia (Firman, 1973), suggests that twenty high stands may be too conservative an estimate. The distribution of the Bridgewater Formation ridges reflects the interplay between complex eustatic influences and a gradually uplifting coastal plain. There have been at least twenty advances and retreats of the Northern Hemisphere ice caps during the Quaternary (C.D. Ollier, pers. comm., 1984), and details of relative changes in the Antarctic ice cap are not well known as yet. In addition, it is not known whether the uplift of the coastal plain was gradual and continuous, or more spasmodic.

Cook & others (1977) concluded that the series of Bridgewater Formation ridges in southeastern South Australia reflects a history of continuous uplift of the coastal region throughout the Plio-Pleistocene, leading to progressive uplift of succeeding sand ridges. They considered that the Pleistocene coastal sequence overall is a sporadic regressive sequence in which repeated eustatic sea-level fluctuations have been imprinted on the gently uplifting coastal plain (Cook & others, 1977). The Bridgewater Formation represents the beach–dune (sand ridge) facies of this environment, whereas the estuarine–lagoonal and fluvio-lacustrine (inter-ridge flat) facies is represented by the Padthaway Formation.

As mentioned previously, the ridges of the Bridgewater Formation in South Australia have significantly and progressively lower carbonate contents with increasing age. Cook & others (1977) thought that this was possibly due to the contribution of sediment to the older ridges from the quartzose Pliocene sand eroded from the eastern part of the coastal plain, or due simply to the increasing age (and hence increased leaching of carbonate) of ridges towards the east. A large part of the carbonate in the Bridgewater Formation is skeletal detritus, and the availability of this bioclastic carbonate is unlikely to have varied greatly during the time of deposition of the coastal ridge sequence. In contrast, variations in quartz content could also reflect variations in sediment input from hinterland rivers due to shifting offshore currents or climatic changes. Variations in rainfall, for example, may have resulted in lesser or greater amounts of sand reaching the Southern Ocean via the Murray–Darling River and other systems, with the result that the Bridgewater Formation dunes would have received varying amounts of sand.

The modern beach–dune complex of the Younghusband Peninsula (see 'Semaphore Sand') is a direct analogue of the Pleistocene beach–dune complexes of the Bridgewater Formation; it also has a high carbonate content.

Stratigraphic nomenclature and type section. The Bridgewater Formation occurs in both the Murray and Otway Basins. The name Bridgewater Formation was first proposed by Boutakoff & Sprigg (1953, their p.40), and it was defined as the lower formation of the Follett Group (Otway Basin) in southwestern Victoria. The Bridgewater Formation is named after Cape Bridgewater, near the town of Portland. Boutakoff & Sprigg (1953) did not define a type section, although Boutakoff (1963) nominated Bridgewater Lakes as the type locality. For the purposes of this Bulletin, the general Bridgewater area of the Otway Basin can be regarded as the 'type area' for the Bridgewater Formation. The nomenclature is complicated by the fact that Boutakoff (1963, his p.34) used the term 'Bridgewater volcanic group' to describe the composite Cape Bridgewater volcano and associated caldera.

Boutakoff & Sprigg (1953) defined two members of the Bridgewater Formation in Victoria: a lower one, 8 m thick, of "flaggy limestones with interbedded pink silt and grey silt soil horizons containing land mollusca", and an upper one, 41 m thick, of "calcareous dunes and dune limestones (aeolianites)". In the same area, Kenley (1971) did not subdivide the formation. In South Australia, Firman (1967a) divided the Bridgewater Formation into upper and lower members, a usage which was continued by Rogers (1980a).

Stratigraphic relationships. The Bridgewater Formation overlies a number of Tertiary and Lower Pleistocene sediments in both the Murray and Otway Basins, and also overlies Lower Pleistocene 'Newer Volcanics' (TQv) in the Gambier Embayment; only its stratigraphic relationships in the Murray Basin (including the Buccleuch Embayment) are described here.

The Bridgewater Formation unconformably overlies the Gambier Limestone (including the Naracoorte Limestone Member), and possibly also overlies the Mannum Formation in places, although

most of the latter unit was eroded from the Buccleuch Embayment in the Early Pleistocene. In the area to the west of Naracoorte, Cook & others (1977) found the Bridgewater Formation disconformably overlying an unnamed Pliocene sand, the lower part of which they correlated with the Loxton Sands. The formation also disconformably overlies the Lower Pleistocene Coomandook Formation; it was also deposited on and abutted topographic highs of the Padthaway Ridge, composed for the most part of Ordovician granites, although Rogers (1980a) recorded Bridgewater Formation overlying a part of the Padthaway Ridge which consists of Miocene 'Gambier Limestone equivalents' onlapping an island of granitic basement.

The Bridgewater Formation interfingers with and is also partly overlain by the lagoonal and inter-ridge deposits of the Padthaway Formation and associated unnamed lacustrine sediments. It is unconformably overlain by several Upper Pleistocene and Quaternary units, including the aeolian Molineaux Sand, the St. Kilda Formation and other lacustrine deposits, and the modern beach-barrier complex (the Semaphore Sand) and back-barrier lagoon (the Coorong). Various calcretes and pedoderms are also associated with the Bridgewater Formation, including the Ripon Calcrete, the Bakara Calcrete, and the Peebinga Soil (Rogers, 1980a).

Correlations. The Bridgewater Formation and its facies equivalent, the Padthaway Formation, are partial correlatives of a number of Upper Pleistocene units within the Murray Basin. These include the upper Blanchetown Clay and the Bungunnia Limestone (both of which are associated with Plio-Pleistocene Lake Bungunnia), the fluvial Shepparton Formation, the colluvial Pooraka Formation, and the aeolian Woorinen Formation. The Bridgewater Formation is primarily a geological unit of the Murray and Otway Basins, but has also been correlated with Pleistocene coastal dunes on Yorke Peninsula, South Australia.

Hydrogeology and economic geology. The Bridgewater Formation is a surface and near-surface entity, located peripherally in a hydrologic sense to the main aquifer systems of the Murray Basin, with which it is not directly connected. The presence of groundwater within the Bridgewater Formation is dependent upon local intake (O'Driscoll, 1960), and groundwater is of high quality where present, but distribution is patchy. In this region, the high rainfall and low topographic elevation result in a shallow water table. This locally reaches the surface in winter (O'Driscoll, 1960), particularly in the inter-ridge sediments of the Padthaway Formation, whereas the upper part of the Bridgewater Formation acts as a recharge zone. Where dunes of the Bridgewater Formation form topographic rises, they are associated with local rises in the groundwater table (Waterhouse, 1977, his fig. 8).

The main hydrologic significance of the Bridgewater Formation is as a highly porous and permeable intake zone. Roberts (1968b) recorded an instance where a fossil groundwater discharge zone within a Padthaway Formation inter-ridge corridor could be related directly to intake from a Bridgewater Formation ridge, i.e. the East Avenue Range near Robe.

The Bridgewater Formation does not contain any known economic mineral deposits, but there is some limited potential for heavy minerals in the beach-deposited facies (see Chapter 15). Colwell (1979) found that concentrations of heavy minerals are generally low, partly as a result of the high content of locally derived biogenic carbonate.

Data sources. The Bridgewater Formation is described in publications by Tindale (1933), Crocker & Cotton (1946), Hossfeld (1950), Sprigg (1952a, 1952b), Boutakoff & Sprigg (1953), O'Driscoll (1960), Boutakoff (1963), Firman (1967a, 1967b, 1972, 1973), Roberts (1968b), Rochow (1969), Kenley (1971, 1976b, 1988b), Colwell (1976, 1978, 1979), Cook & others (1977), Waterhouse (1977), Idnurm & Cook (1980), Rogers (1980a), and Von der Borch & others (1980).

Unit: Padthaway Formation
Age: Early to Late Pleistocene
Map symbol: Qcl

Lithology. The Padthaway Formation is a composite geological unit consisting of the bulk of the inter-dune corridor sediments of the coastal region of southeast South Australia. Clastic components of the Padthaway Formation are unconsolidated, and include variegated clay, sandy clay, calcareous clay, minor quartz sand and shell detritus. The only lithified components of the Padthaway Formation are white to pale-grey, fine-grained lagoonal to freshwater dolomite and limestone. Unconsolidated, dark, reducing, lacustrine mud and local peat are also included in the formation.

Distribution and thickness. The Padthaway Formation occurs in both the Buccleuch Embayment of the Murray Basin and the Gambier Embayment, in southeastern South Australia and southwestern Victoria; it is distributed between the stranded coastal

ridges of the Bridgewater Formation, and incorporates all the inter-ridge sediments with the exception of the Holocene aeolian Molineaux Sand (Fig. 128). As would be expected, the thickness of the Padthaway Formation is variable: Rogers (1980a) recorded thicknesses of 7 m or less on PINNAROO; however, Stephenson (*in* Brown & Stephenson, 1986) found that the Padthaway Formation attained a maximum thickness of 47 m on PINNAROO and over 50 m on NARACOORTE. Thickness range is mostly between 5—20 m, but greater thicknesses are not unusual.

Geometry, topography, and vegetation. The Padthaway Formation forms elongate and narrow inter-dune corridors subparallel to the modern coast of South Australia (Figs 92, 128). These inter-dune corridors take the form of flat and very low-lying plains, with numerous wetlands, small lakes, and some small lunettes. Large areas of these wetlands have been partly drained by man-made canal systems (Rochow, 1969). The natural vegetation is dominated by low trees, low shrubs, and tussock grasses, but the Padthaway plains are utilised quite heavily for sheep and cattle grazing, and many inter-dune corridors are now mainly covered by grasses.

Palaeontology. No detailed study of the palaeontology of the Padthaway Formation has as yet been published, although Cook & others (1977) recorded the presence of coquinas and scattered individuals of the gastropod *Coxiella striata*, which they took to indicate saline conditions; this is the same gastropod as the *Coxiella confusa* described by Sprigg (1952a) from higher salinity areas of the Padthaway Formation. Sprigg (1952a) noted that the modern freshwater lakes, marshes, and lagoon systems associated with the Padthaway Formation abound in freshwater snails, with the genera *Limnea, Corbiculina, Lenameria,* and *Sphaerinova* being particularly well represented in the fauna.

Sprigg (1952a) was of the opinion that the sea had invaded the western part of the South Australian coastal plain at some time late in the Pleistocene, and he related two distinct faunas to this short transgression. On the seaward side of islands and peninsulas, the bivalve genera *Katelysia* and *Chione* were dominant within the Bridgewater Formation, whereas associations of *Anadara (Arca) trapezia* and *Ostrea* (oysters) choked the mud flats on the lee sides of the partially submerged dunes (Sprigg, 1952a). Both these fossil shell associations can thus be found in the more-westerly of the Padthaway Formation inter-dune corridors.

Age evidence. The evidence for the age of the Padthaway Formation is derived from its genetic association with the Bridgewater Formation. Like the Bridgewater Formation, the inter-dune corridors of the Padthaway Formation are of progressively younger age towards the modern coast; however unlike the beach—dune sequence, fluvial and lacustrine sedimentation continued at the top of the Padthaway Formation long after the original back-barrier lagoon was infilled: swamp and lacustrine sedimentation is continuing today in some inter-dune corridors underlain by the Padthaway Formation.

The oldest Pleistocene coastal lagoonal sediments are the Qpu dolomites of the Buccleuch Embayment, which are some 0.8 to 0.9 Ma old (see 'Qpu'); the oldest Padthaway Formation corridor lies between the Pinnaroo Block and the oldest, most easterly Bridgewater Formation ridge near Bordertown. Based on magnetic reversals (Cook & others, 1977), the Padthaway Formation corridors associated with the most-easterly four dune ridges in this area are all older than 0.69 Ma, but all dune corridors west of the Naracoorte Ranges are less than 0.69 Ma old (see discussion on the age of the Naracoorte Ranges in 'Bridgewater Formation').

Characteristics. The Padthaway Formation is characterised by its geographic and stratigraphic position, varied lithologies, and geomorphic expression as flat inter-dune plains.

Environment of deposition. Each package of Padthaway Formation inter-dune sediments was deposited in a range of environments, ranging from semi-restricted marine lagoons, through marginal restricted lagoons, ephemeral salt lakes, and fluvial and intermittent fresh-water lacustrine environments, to marshes, peat swamps, and lakes. The Padthaway Formation was thus deposited in environments partly analogous to those of the modern Coorong and its southern extensions (Firman, 1973). The Padthaway Formation also includes some outwash deposits of clay and sandy clay, adjacent to the Pinnaroo Block on NARACOORTE (Rochow, 1969).

Stratigraphic nomenclature and type section. In his early work on the coastal dune sequence, Sprigg did not name the inter-dune sediments now known as the Padthaway Formation, and referred to them simply as 'inter-dune corridors' (Sprigg & others, 1951; Sprigg, 1952a, 1952b). Similarly, Rochow (1969) did not name the sediments. Harris (1973) referred informally to inter-dune dolomite, sand, and clay as the 'Padthaway Formation', and this usage was continued by Rogers (1980a). Firman (1973) referred to *Anadara* shell banks adjacent to the Woakwine Dune as 'Glanville Formation', but this usage has been

restricted to estuarine sediments with shell banks by Rogers (1980b) on his map of southeastern South Australia; Rogers (1980b) retained the term Padthaway Formation for the inter-ridge corridor lagoonal and fluvio-lacustrine sediments. Harris (1973) described a basal clay unit of the Padthaway Formation as the 'Keppoch Member', but this appears to be a local unit, and only one occurrence is known on PINNAROO (Rogers, 1980a). No type section has yet been formally defined for the Padthaway Formation.

Stratigraphic relationships. The Padthaway Formation is a partial facies equivalent of the Bridgewater Formation, and overlies and interfingers with coastal beach and dune sands of that formation. The Padthaway Formation is, in turn, locally and conformably overlain by aeolian deposits of the Molineaux Sand, and by modern lacustrine deposits (Ql). Calcretes (Qca), in particular the Bakara Calcrete, are locally developed on top of the Padthaway Formation (Rogers, 1980a). South of the Coorong, modern lagoonal sediments (Qhl) grade into older inter-dune sediments presently included in the Padthaway Formation.

Correlations. The Padthaway Formation is a partial facies and time equivalent of the Bridgewater Formation. It is also partly time-equivalent to a number of other Murray Basin units, including the fluvial Shepparton Formation, and the aeolian Woorinen Formation and associated units. The Padthaway Formation also occurs in the Otway Basin of western Victoria, although it is not known by any formation name. Kenley (1971, 1976a, 1988a) described the Bridgewater Formation and the inter-dune sediments in that area.

Hydrogeology. The Padthaway Formation is normally saturated to the surface, or near-surface, with shallow groundwater, which is related to local recharge from rain falling not only on the inter-dune corridors, but also on the adjacent Bridgewater Formation dune ridges (O'Driscoll, 1960; Roberts, 1968b). Regional man-made drainage schemes have considerably lowered the water table in many Padthaway Formation inter-ridge corridors (Roberts, 1968b).

Data sources. The Padthaway Formation is described in publications by Sprigg & others (1951), Sprigg (1952a, 1952b), O'Driscoll (1960), Roberts (1968b), Rochow (1969), Kenley (1971), Firman (1973), Harris (1973), Cook & others (1977), Rogers (1980a, 1980b), and Brown & Stephenson (1986). Equivalent sediments in the Otway Basin have been described by Kenley (1976a, 1988a).

Unit: Woorinen Formation
Age: Quaternary, mainly Late Pleistocene with minor re-mobilised Holocene components
Map symbol: Qdw
Component members: Miralie Member, Bymue Member, Speewa Member, Kyalite Member, Piangil Member (Table 35)

Lithology. The Woorinen Formation consists mainly of red-brown siliceous silty sand, red calcareous silty clay, and sandy clay. It characteristically contains well-developed horizons of platy and nodular calcrete. Younger components are mainly pale orange-red and have a lower clay content, whereas older components are brick-red and have undergone a high degree of pedogenesis. The sand and silt components are locally admixed with clay pellet aggregates, and humic material consisting of leaf litter, twig debris and remnant rootlets. The sand component consists of medium to fine-grained quartz grains, stained by sesquioxides and red clay cutans. The unit is largely unconsolidated, but has been subject to varying degrees of pedogenesis, which has resulted in a minor degree of consolidation of sand grains by interstitial clays. A few carbonaceous laminae are present, as well as rare thin interbeds of charcoal indicating the former occurrence of fire. Red palaeosols, with sandy loams and sandy clay loams, are distributed throughout the formation and are associated with each of the component members, with the exception of the uppermost member. The degree of clay mobilisation and leaching of calcite increases with the age of each of the soil profiles. In places, the formation has fragmented tap root and filamental rhizoliths, and characteristically has soft gypsiferous glaebules, and soft to hard carbonate glaebules up to several centimetres in diameter. With depth, these grade to cemented calcrete hardpans, which locally coalesce to form massive brecciated sheets of calcrete rubble towards the base of the unit (see descriptions of calcrete – 'Qca'). The thicker calcretes are probably composite beds consisting of a number of superimposed profiles. Chemical and X-ray diffraction analyses of the calcretes indicate that they consist of between 55–70% calcite, 1–9% dolomite and 17–40% iron and aluminium oxides (table 9 of Lawrence, 1975). In many places, they also have a high silica content. The unit forms aeolian dunes and swales, within which Churchward (1960) found that the salt content of associated soils increases progressively from the sandy soils dominant at dune crests to the clays which predominate within the intervening swales.

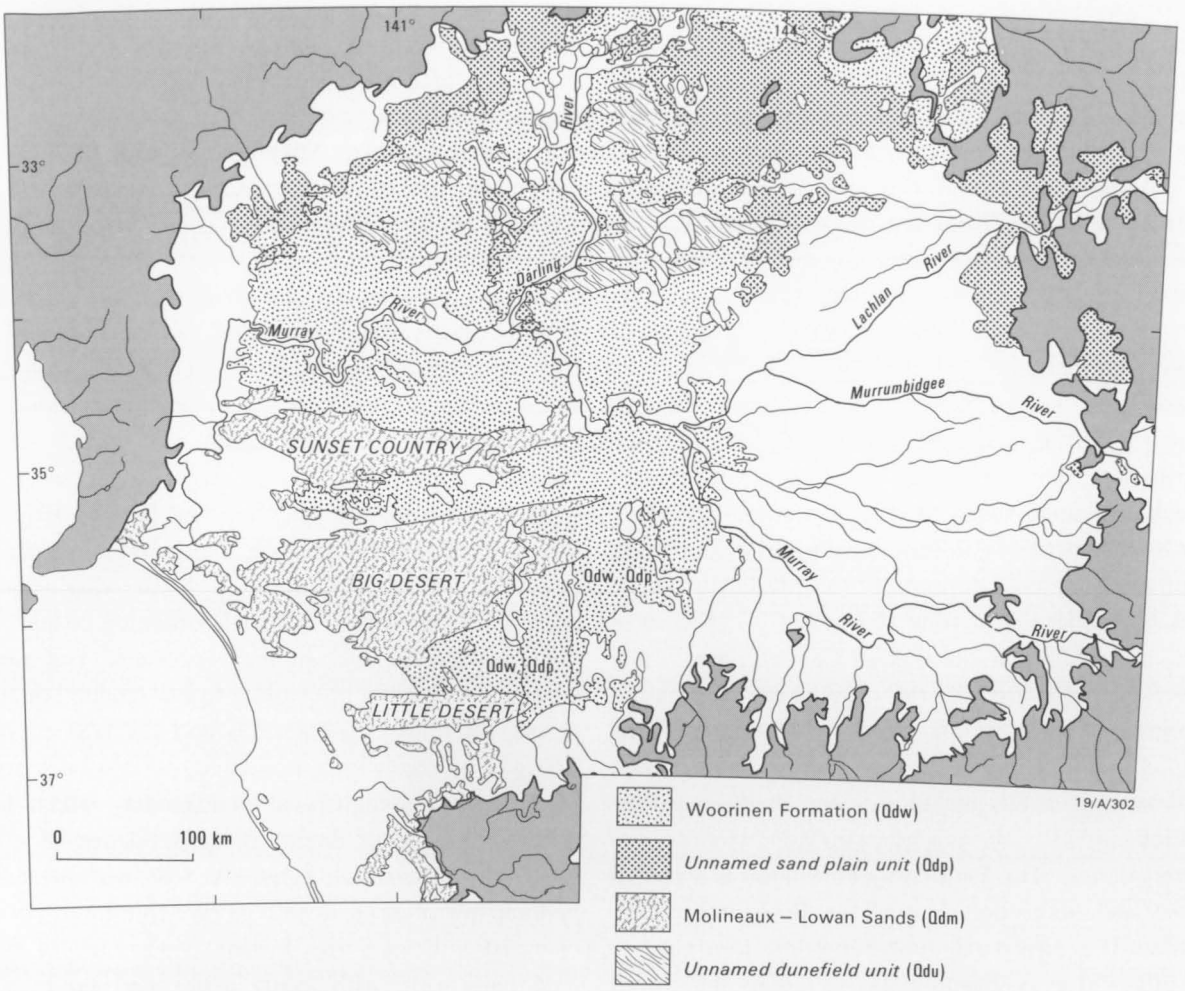


Fig. 130. Distribution of Quaternary aeolian morphostratigraphic units of the Murray Basin – Woorinen Formation (Qdw), Molineaux–Lowan Sands (Qdm), and unnamed Qdu and Qdp units.

Distribution and thickness. The Woorinen Formation is widely distributed, underlying much of the aeolian landscape of the Mallee Region of the western Murray Basin (Fig. 130). The unit is also found in many places along the northern flanks of the basin, and in small isolated dunefields located towards the western and eastern margins of the Riverine Plain. The thickness of the unit is highly variable, but it generally is a thin blanket of sediment 2–3 m thick, with dunefields being locally considerably thicker. North of the Murray River, west of the Darling Anabranch, for example, the formation forms a thin veneer over Blanchetown Clay. Elsewhere, individual dunes can be several metres high, whereas the sediment in adjacent intervening swales may be less than 1 m thick.

Outcrop and geomorphic expression. Throughout much of its area of distribution, the Woorinen Formation is preserved as extensive dunefields and sand sheets characterised by discontinuous chains of east–west-oriented longitudinal dunes (Fig. 131). Dunefields are particularly well developed in western and central areas of the basin. Towards the southern and northern margins of the basin, the dunes become increasingly subdued, form low mounds, and are eventually replaced by a featureless sand sheet. In northern areas of the basin, an extensive area, lacking in sand dunes, has been differentiated as a separate unnamed unit (Qdp), but in the south smaller areas of lithologically similar sheet deposits of sandy/silty clay were included in the Woorinen Formation by Lawrence (1975). Individual dunes within the fields have been extensively eroded, and are characterised by subdued and rounded crests, and low-angle flanking slopes. A number of dune morphologies are preserved. The most characteristic has been described as elongate tear-drop or cigar-shaped. These form extensive dunefields in northwest Victoria and adjacent areas of South Australia and New South Wales (Figs 14, 130–132). In many areas, the original dune morphology has largely been smoothed by deflation (Figs 133, 134). Individual

Fig. 131 Photomosaic of Danyo and Underbool 1:100 000 Sheet areas, showing dunefields of Molineaux–Lowan Sands (Qdm) forming Big Desert in south and Sunset Country in north (dark vegetated areas), separated by east-west dunes of Woorinen Formation (largely cleared for wheat fields). Ragged light-coloured, northeasterly trending areas within Big Desert are former fire burns.

dunes are separated by broad swales, and clusters of dunes are commonly separated by flat sand plains or areas of low hummocky dunes. Some of the interdune sand plains are former fluvio-lacustrine areas (inactive groundwater discharge complexes in places), blanketed by a thin veneer of aeolian silty sand and clay pellets.

The larger individual dunes are a few hundred metres to 1 km in length, up to 100 m wide, and many are only a few metres in height (up to 10 m, but generally 2–3 m). Transverse profiles are normally asymmetric, with a southern slope that is slightly steeper than the northern slope. Older components of the formation are aligned almost exactly east–west, whereas, younger or reworked elements are oriented west-southwest to east-northeast. Within younger components of the formation, the dunes are less regular in orientation and are locally transitional with the irregular dune morphologies of the Molineaux–Lowan Sands (Qdm) and unnamed Qdu units. The finer-grained sediments of the swales are locally associated with deflated lacustrine and former groundwater discharge sites, though in places they are related to poorly preserved internal drainage patterns within the dunefields. The dunefields lack a coordinated internal drainage system, although in places partly buried remnants of former drainage channels can be traced for several kilometres. In many cases, the location of former water courses is marked by strings of small areas of fluvio-lacustrine sediments within the intervening swales. Parts of the dunes are highly permeable, and the ground surface dries rapidly after rains, although, beneath both dunes and swales, clay and calcrete palaeosols, and near-surface well-cemented calcrete sheets, are locally highly impermeable (Fig. 124).

Internal geometry. Steeply dipping sets of cross-bedded sands are preserved in the younger components of the Woorinen Formation, but in older components internal sedimentary structures have largely been destroyed by pedogenesis, and by intrusion of the characteristically deep and extensive root systems of the Mallee vegetation. In some dunes, individual members can be identified. In many instances, older members were eroded and truncated prior to deposition of younger members (Lawrence, 1976a, 1988a). Younger members mantle the older components, but were progressively displaced to the east and south relative to the older components, during deposition (Fig. 134). Deeper levels of the formation contain carbonate rhizoliths and rhizocretions, some of which are vertically oriented tap roots, while others are subhorizontal secondary rhizoliths. Over large areas of the basin, but particularly in western areas, the base of the Woorinen Formation is marked by the presence of a calcrete hardpan (e.g. Gill, 1974; see also 'Calcrete' – Qca). In many places, this consists of a re-cemented white or pale-grey brecciated calcrete, cross-cut by irregular anastomosing veins and fracture planes infilled with red-brown silty sand. Brecciation of the calcrete hardpan is locally associated with the intrusion of tree-root systems.

Palaeontology. The formation has abundant leaf and twig debris, as well as charcoal and intruding rootlet material. It also has both whole and comminuted remains of shells of land snails and abundant fragmented bones of marsupials, as well as bones of introduced mammals such as rabbits and foxes.

Age evidence. Little direct evidence of the age of the Formation is available. As noted elsewhere, palaeomagnetic data from the underlying Blanchetown Clay suggest that the aeolian landforms of the western Murray Basin initially developed between 0.4–0.7 Ma. The identification of a number of members, separated by palaeosoils suggests several phases of mobilisation over the past 0.5 Ma; the high clay content, rubification of quartz sand grains, calcrete development, degree of erosion, and orientation of dunes all suggest that the oldest components of the Woorinen Formation date from the initiation of major aridity. Radiocarbon dates obtained by Bowler & Polach (1971) ranged from 15 500 to 30 000 yrs. B.P., but gave only minimum ages for older components of the formation. The well-preserved dune morphologies of the younger components indicate that they are of relatively recent origin, whereas the youngest component (Piangil Member) is currently mobile. As reported by Bowler (*in* Magee & Beaton, 1985) and by Readhead (1988), thermoluminescence ages of 22 000 to 28 000 yrs. B.P. were obtained from the Kyalite Member, and ages of 12 000 to 14 000 yrs. B.P. from the Speewa Member in a railway cutting near Nyah West (Churchward, 1963a,b,c; Rowan & Downes, 1963). Both these soil-stratigraphic units occur in the upper portion of the dune, and at least four older calcareous palaeosoils are known from the Nyah West site. In the Willandra Lakes region, as noted by Bowler & Wasson (1984), the dunes of the Woorinen Formation do not extend over the lake floors and were trimmed back by surface waters. The Willandra Lakes were last active some 14 000 yrs. B.P., and hence the youngest major mobilisation of the dunefields in this area appears to predate this time, and is thought to have occurred from about 20 000 to

Fig. 132. LANDSAT scene showing dunefields of northwestern Victoria – irregular dunes of the Molineaux–Lowan Sands (Qdm) form the Sunset Country, Big Desert, and little Desert (dark areas of generally uncleared natural vegetation). East–west oriented dunes of the Woorinen Formation (Qdw) underlie much of the area cleared for cultivation (mainly wheat fields). Northwesterly trends, which can be seen between the Little Desert and the Big Desert, represent concealed remnant ridge and swale morphology of the underlying Pliocene Loxton–Parilla Sands (Tps), blanketed by Quaternary aeolian dune deposits.

16 000 yrs. B.P. (Bowler, 1978b).

Characteristics. In comparison with the younger yellow siliceous sands of the Molineaux–Lowan Sands, the Woorinen Formation contains a high calcareous clay and silt content and consists of rubified sand grains. The formation also characteristically has several palaeosoils and is underlain by well-developed calcrete. Dune forms are generally subdued and rounded, in comparison with the Molineaux–Lowan Sands. The rubified quartz sand component of dunes of 'Qdu' is lithologically similar to that of the Woorinen Formation, but 'Qdu' sands have less clay and lack calcrete, and its dune forms are morphologically similar to those of the Molineaux–Lowan Sands.

Interpretation of environment of deposition. The sediment of the Woorinen Formation dunes and swales was deposited in an aeolian environment, and was subsequently modified by pedogenesis and fluctuating groundwater tables. Several modes of formation have been proposed to explain both the source of the aeolian sediment and the morphology of the dunes. Lawrence (1966) suggested that the east–west orientation of the tear-drop dunes indicated initial deposition by winds blowing predominantly from the west, whereas the orientation of younger components suggests a slight shift to winds from the west-southwest. The orientation of the youngest components is thus coincident with present dominant wind regimes from the west-southwest. Bowler & Magee (1978) suggested that the clay content of the dunes can be explained by a process of deflation in the intervening swales. In particular, they suggested that saline efflorescence in poorly drained and salinized swales resulted in the breakdown of clay into clay pellet aggregates, which were then exposed to deflation, resulting in the aeolian transportation of sand-size aggregates to the flanks and crests of adjacent dunes. Both the dune and swale morphologies are thus thought to have been maintained by deflationary processes in the intervening swales.

At present, dunes of the Woorinen Formation are vegetated by low Mallee scrub, and with the exception of the younger components and some areas now cleared for agriculture, the dunes are stabilized. This suggests that the dunes were deposited during intervals when conditions were marginally more arid than those currently prevailing, and partly also during periods when groundwater tables were higher than those of today. Most authors now relate this aridity to periods of glacial maximum when conditions were cold but dry (e.g. Galloway, 1965), rather than to hot and arid periods. If the vegetation cover was sufficiently sparse, rainfall (despite being low) may have maintained high groundwater levels by recharging the underlying aquifers, rather than being intersected by vegetation. Bowler & Wasson (1984) related development of clay-pellet dunefields to the hydrologic conditions that prevailed during phases which were transitional between humid lacustral conditions and arid aeolian-dominated conditions. They suggest that during the transitional period, surface water volumes diminished and became more saline, and that saline groundwaters may have discharged into swales and predominated over surface runoff – resulting in seasonal efflorescence of salts, development of sand-size clay pellets, followed by deflation and deposition of the mixed sand and clay dunes of the Woorinen Formation. The remobilisation of quartz dunes can be related to periods of aridity, when groundwater tables were sufficiently far below the ground surface to prevent development of pelletal clay aggregates. Stabilizing vegetation cover may have become sparse and the dunes mobile. The local absence of clay-pellet components can therefore be related to a lack of groundwater involvement at particular times in some areas. During summer droughts at the present-day, hot dry winds originating in the continental interior sometimes result in the mobilisation of sand and development of major dust storms (e.g. Chapman & Grayson, 1903). The drifting sand deposits of these storms are referred to the Piangil Member of the Woorinen Formation in Victoria, but are included in the Molineaux Sand in South Australia.

The Woorinen dunefields are best developed in western areas of the basin, underlain by the Loxton–Parilla Sands (Tps) – the deflation of which provided the primary source of quartz sand. Similarly, deflation of the Blanchetown Clay (Qpc) was probably responsible for the clay content of the Woorinen dunes.

Stratigraphic nomenclature. The formation was named by Lawrence (1966) after the township of Woorinen in SWAN HILL.

Type section. The type locality of the unit is in Allotment 8, Section B, Parish of Tyntynder in SWAN HILL (Lawrence, 1966; Churchward, 1960, 1961, 1963a,c; Fig. 134; Table 35). In this area, the formation consists of east–west dunes separated by extensive areas of parna clay plain.

Stratigraphic relationships. In western areas of the basin, the Woorinen Formation forms a blanket deposit which disconformably overlies Blanchetown Clay, Bungunnia Limestone and buried ridge and

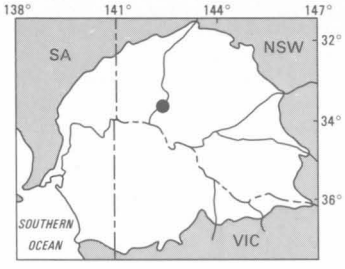


Fig. 133. Aeolian dune of Woorinen Formation with characteristic Mallee vegetation; east of Darling River (ANABRANCH).

inter-ridge sediments of the Loxton–Parilla Sands. Around the northern and southern areas of the basin, and beneath parts of the Riverine Plain, the formation disconformably overlies fluvial sediments of the Shepparton Formation. Towards the northwestern margins of the basin, the unit also overlies and is partly intercalated with the upper part of the Pooraka Formation. In erosional gullies around, the margins of saline lakes the formation has been found to partly overlie, but also to be partly intercalated with gypsiferous saline lake deposits of the Yamba Formation. Modern saline and non-saline lake deposits are locally incised within older components of the Woorinen Formation. The younger fluvio-lacustrine sediments of the Murray and Darling Rivers are also entrenched within the formation. Calcrete sheets, which have been locally differentiated as separate units are best developed at the base of the unit in western areas (e.g. Ripon Calcrete of Firman, 1973), although nodular carbonate horizons are also associated with a number of palaeosols within the formation.

Churchward (1960) identified a number of soil-stratigraphic layers (Fig. 134), which Lawrence (1966) adapted as five members within the Woorinen Formation in Victoria (Table 35). In South Australia, Firman (1973) included only the lower three of these component members in the Woorinen Formation, and included the upper two in the Molineaux Sand. The regional applicability of the sub-divisions of the Woorinen Formation in the Swan Hill region has not yet been tested elsewhere in the basin.

Aquifer characteristics. The unit does not form part of any of the major regional aquifer systems of the basin, although as discussed above the morphology and characteristic clay content of the dunes reflect

TABLE 35. COMPONENT MEMBERS OF THE UPPER PLEISTOCENE – HOLOCENE WOORINEN FORMATION

Unit: Miralie Member of Woorinen Formation

Age: Late Pleistocene

Map symbol: included in Qdw

Synonym: Tooleybuc Layer

Lithology. Dark-red, mottled, plastic clay and sandy clay; firm and dense, but deeply weathered and, unlike overlying units, leached and lacking lime. Churchward (1963a) noted bimodal fine and coarse sand particle size beneath swales, and unimodal coarse sand size higher up buried slopes of adjacent dunes.
Distribution, thickness, outcrop and geomorphic expression. In type area forms substrate to most overlying units, and occurs within core of major dunes as well as extending beneath adjacent swales. Rises to higher levels within dunes than in swales, but does not reach crest of dunes and tends to be thicker towards west-end of dune, suggesting lateral extension of dune achieved by accretion of subsequent layers to protected east and southeast slopes. Depositional features largely obliterated by subsequent soil development.
Age evidence. Age not known, but older than Speewa Member which has tentatively been assigned age range 120 000 – 140 000 yrs. B.P. (Bowler, in Magee & Beaton, 1985). Not, however, oldest known soil stratigraphic layer and, therefore, likely to be considerably younger than initiation of arid landforms between 0.4 – 0.7 Ma.
Environment of deposition. Churchward (1963a) suggested Miralie Member aeolian parna with associated aeolian fine sand, with coarser-grained sand locally emplaced by saltation.
Stratigraphic nomenclature, synonyms and type Area. Named by Lawrence (1966) after township of Miralie 28 km NW of Swan Hill (SWAN HILL). Miralie Member of Lawrence (1966) synonymous with Tooleybuc layer of Churchward (1960, 1961, 1963a, 1963b). Type area in Woorinen Settlement area (SWAN HILL), where Churchward (1960) first described 'Tooleybuc Layer' (Fig. 134). Also exposed in railway cutting at Nyah West (Bowler, in Magee & Beaton, 1985).
Stratigraphic relationships. In type area disconformable under Bymue or Speewa Member. Locally overlies older un-named components, but elsewhere directly overlies Loxton – Parilla Sands or Blanchetown Clay.

Unit: Bymue Member of Woorinen Formation

Age: Late Pleistocene

Map symbol: included in Qdw

Synonym: Bymue Layer

Lithology. Weathered, calcareous, red-brown, clayey sand and sandy clay on dunes, grading to predominant heavy clay beneath adjacent plains. Soil component have well-developed peds and segregated calcareous horizons. Soil segregation occurs at greater depth than in overlying Speewa Member. Calcareous material forms firm and coherent hard pan or concretions. Clays dense and firm with glossy clay faces (Churchward, 1960). Original depositional features largely obscured by subsequent development of soil profile.
Distribution, thickness, outcrop and geomorphic expression. Thickness 10 – 60 cm on north and west dune slopes, but can thicken to about 1.8 m on upper south and east slopes. Where present, over intervening sand plains, unit commonly 80 – 120 cm thick.
Age evidence. Sample from Bymue Member yielded radiocarbon age of 29 750 ± 1200 – 1450 yrs. B.P. (Bowler & Polack, 1971); however, uncertain thermoluminescence dates > 140 000 yrs. B.P. obtained from overlying Speewa Member (Bowler, in Magee & Beaton, 1985).
Stratigraphic nomenclature, synonyms and type section. Named by Churchward (1960) after Parish of Bymue, N.S.W. Bymue Member of Lawrence (1966) synonymous with 'Bymue layer' of Churchward (1960, 1961, 1963a, 1963b). Type section located at crest of east – west oriented dune, 13 km northeast of village of Tooleybuc (BALRANALD).
Stratigraphic relationships. In type area disconformable over Miralie Member and disconformable under either Speewa or Kyalite Member.

Unit: Speewa Member of Woorinen Formation

Age: Late Pleistocene

Map symbol: included in Qdw

Synonym: Speewa Layer

Lithology. Dominant yellow-brown to reddish brown calcareous sand, with red clay matrix; strongly weathered and capped by well-differentiated soil profile with calcrete development in 'B' horizon. Lawrence (1966) noted unit sandier in NW than southeast of Mallee region in Victoria. NW of Swan Hill, Churchward (1963a) found sand in swales fine and medium-grained, whereas on ridge crests mainly coarse-grained – also noted lime leached from upper 35 cm, and lime (calcrete) now in form of concretions as well as fine earth. Original bedding and other depositional features largely obscured by subsequent weathering and formation of soil profiles.
Distribution, thickness, outcrop and geomorphic expression. Much more widespread than overlying Kyalite Member and usually forms surface unit. Where present, generally 20 – 60 cm thick, but locally up to 3 m. Thickest on east and south faces of dunes; thinner on north and west slopes (Lawrence, 1966). Occurs in both crests and swales of east – west oriented dunes; also present in hummocky dunefields of southeast Mallee region.
Age evidence. Age uncertain. Sample yielded radiocarbon date of 24 000 ± 900 yrs. B.P. (Bowler & Polack, 1971). However, Bowler (in Magee & Beaton, 1985) and Readhead (1988) recorded uncertain thermoluminescence age determinations 120 000 – 140 000 yrs. B.P.
Environment of deposition. Forms blanket deposit over dunes and intervening plains. In low-lying areas, disconformable over underlying unit, but on north and west slopes of dunes mantles truncated Bymue Member. Churchward (1963a) interpreted unit as calcareous parna deposit, with aeolian clay aggregates and fine sand derived from areas to west, admixed with saltated coarse sand grains of local origin.
Stratigraphic nomenclature, synonyms and type section. Named 'Speewa layer' by Churchward (1960) after township of Speewa, 13 km north of Swan Hill (SWAN HILL). Name modified to Speewa Member of Woorinen Formation by Lawrence (1966). Type locality exposed in swales flanking east – west oriented dune located in allotments 33, 34, 35, and 36 in Parish of Tyntynder, 8 km north of Swan Hill – occurs within dune but concealed beneath overlying type-section of Kyalite Member.
Stratigraphic relationships. Disconformable over Bymue and older members and disconformable under Kyalite and younger members; forms surface unit of Woorinen Formation in many areas.

Unit: Kyalite Member of Woorinen Formation

Age: Late Pleistocene to ?Holocene

Map symbol: included in Qdw

Synonym: Kyalite Layer

Lithology. Yellow-brown to grey-brown, calcareous, clayey sand. Sand grains in swales very fine-grained, whereas medium-grained in crestal areas of dunes (Churchward, 1963a). Within individual dunes sorting of sand fraction increases from north and west to east and south. Soils poorly differentiated in comparison with older units. Carbonate less abundant than in lower older members, but preserved in upper part of profile, where present in form of fine earth rather than concretions and hardpans. Fragmented calcareous tap roots and filamental rhizoliths not yet leached from upper portions of unit. Depositional features partly destroyed by incipient development of soil profile.
Distribution, thickness, outcrop and geomorphic expression. Forms discontinuous surface layer and occurs as thin capping on east – west dunes and hummocks of Woorinen Formation. Up to 4 m thick in some rail and road cuttings in NW Victoria (Lawrence, 1966), but maximum thickness 1.5 m in Woorinen area (Churchward, 1963a). Thickest on south and east slip faces and thinnest on eroded north and west slopes.
Age evidence. Bowler & Polack (1971) obtained radiocarbon age of 15 500 ± 230 yrs. B.P., whereas Bowler (in Magee & Beaton, 1985) and Readhead (1988) reported uncertain thermoluminescence age

TABLE 35. ctd.

22 000 – 28 000 yrs. B.P.
Environment of deposition. Churchward (1963a) suggested primarily deposited as consequence of aeolian erosion and sorting of underlying Speewa Member, resulting in loss of calcareous material and fine sands, silt and clay components, and concentration of coarser sand fraction in form of drifted sand.
Stratigraphic nomenclature, synonyms, and type section. Kyalite Member (Lawrence, 1966), modified from Kyalite Layer of Churchward (1960, 1963a). Named after Kyalite River (Edwards River) at boundary between BALRANALD and SWAN HILL. Type locality of Kyalite Member on east – west oriented dune located in allotments 33, 34, 35, 36, Parish of Tyntynder (Lawrence, 1966), 8 km NW of Swan Hill.
Stratigraphic relationships. Disconformable under Piangil Member, and disconformable over Speewa or older Members. Equivalents of Kyalite Member in S.A. included in Molineaux Sand by Firman (1973).

Unit: Piangil Member of Woorinen Formation

Age: Holocene

Map symbol: included in Qdw

Synonym: Piangil Layer

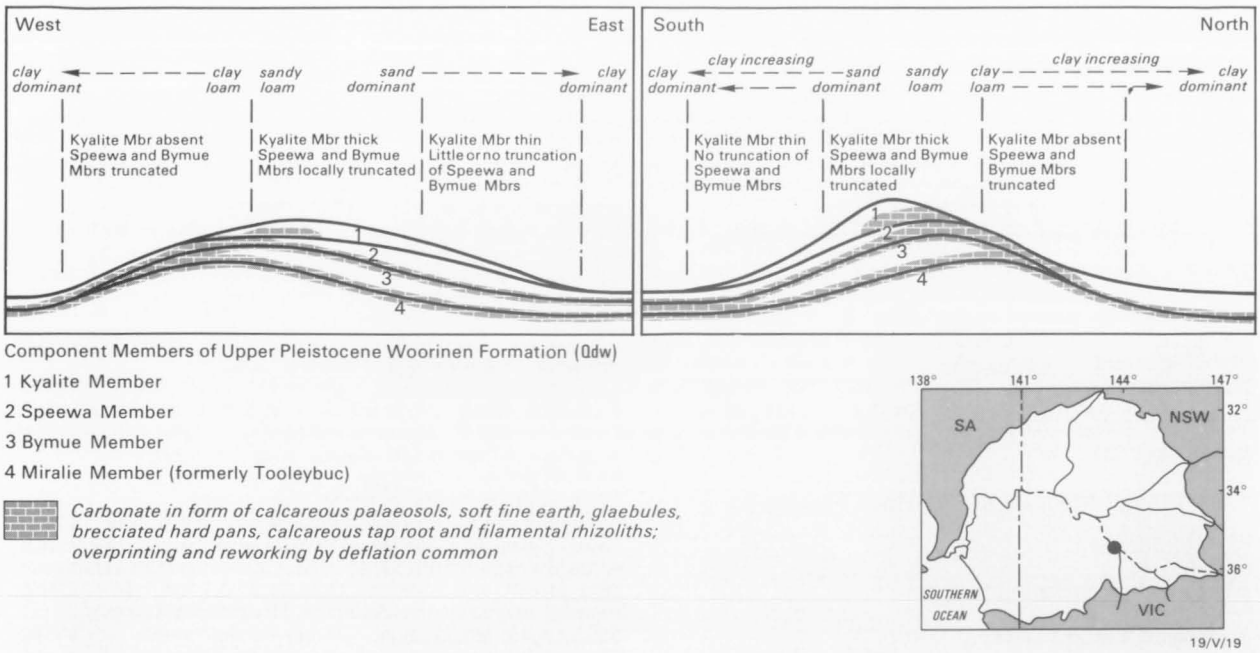
Lithology. Loose, free-flowing sand; mainly pale-yellow to orange. Sand admixed with humic debris and soil clasts, but lacking red clay matrix and calcareous glaebules characteristic of older components of Woorinen Formation. Relatively unweathered, and soil profiles not yet developed. Unlike many older members cross-bedding preserved.
Distribution, thickness, outcrop and geomorphic expression. Widespread throughout Mallee region, but identified mainly in west Victoria. Aeolian dunes of Piangil Member generally only few tens of cm to few m thick. Forms small areas of locally mobile hummocky dunes. Subject to reworking under present-day wind regimes; many deposits assigned to Piangil Member have accumulated against modern fences and buildings as well as against clumps of vegetation.
Age evidence. Uppermost, and consequently youngest, member of Woorinen Formation. In many areas, recent movement of Piangil Member can be demonstrated where sand drifts accumulated against fences or across irrigation ditches and roads. Member, therefore, of very recent origin and still currently mobile.
Environment of deposition. Unlike older members of Woorinen Formation, consists of mobile sand lacking in soil development. Formed by local deflation and redeposition of older components of Woorinen Formation and adjacent units. Recent mobilisations related to periods of drought in areas subject to erosion, due to clearance of vegetation for wheat, sheep grazing.
Stratigraphic nomenclature, synonyms and type section. 'Piangil Layer' named by Churchward (1963a) after township of Piangil, 40 km NW of Swan Hill (SWAN HILL). Lawrence (1966) nominated crest of east – west oriented dune, located 2 km NW of Piangil township as type section (Allotment 142, Parish of Piangil).
Stratigraphic relationships. Mainly disconformable over Kyalite Member, but also overlies older members of Woorinen Formation and other stratigraphic units of Mallee landscape. Equivalent to younger components of Molineaux – Lowan. Sands (mobile components of unnamed aeolian units Qdu and Qdl included in Molineaux Sand in S.A.).

the interactions between surface geomorphic processes and fluctuating groundwater tables. Rainwater usually soaks rapidly into the Woorinen Formation, where it is tapped by the roots of the Mallee vegetation. Where the Mallee vegetation has been cleared, rainwater recharges the underlying Loxton – Parilla Sands, whereas in uncleared areas only a small proportion of rainwater recharges the underlying shallow aquifer. The unit locally forms a perched aquifer where underlain by the Blanchetown Clay, and also above some of the thicker sheet calcretes. Local perched aquifers also occur above some of the more impermeable illuvial horizons within some of the dunes.

Data sources. Descriptions of the geomorphic and soil characteristics of the formation are provided in Churchward (1960, 1961, 1963a,c), and Rowan & Downes (1963). Geologic descriptions of the unit and interpretations of modes of formation are in Lawrence (1966, 1975, 1976a, 1980, 1988a), Bowler & Polach (1971), Firman (1973), Bowler & Magee (1978), and Magee (1986). Additional descriptions of profiles through the Woorinen Formation are in Gill (1973a, 1974).

Component members of the Woorinen Formation

The Woorinen Formation is a composite aeolian deposit which accumulated during a number of phases of mobilisation separated by extended phases of dune stabilization accompanied by soil profile development. Illuvial calcareous soil horizons separating siliceous intervals were first described by Hills (1939). The soils and profiles of the Woorinen Formation were subsequently mapped in detail at several localities near Swan Hill by Churchward (1960, 1961, 1963a,b,c), who identified a number of superimposed layers, each thought to have been deposited during separate phases of accretion, and each separated by palaeosol horizons (Fig. 134). He named these, from youngest to oldest: the 'Kyalite layer', 'Speewa layer', 'Bymue layer', and 'Tooleybuc layer'. Churchward (1963a) also differentiated the products of modern aeolian drift, which he named the 'Piangil material'. Lawrence (1966) subsequently modified these soil-stratigraphic units and converted them into members of the Woorinen Formation (Table 35). The Tooleybuc layer was re-named to Miralie Member to avoid confusion with an existing stratigraphic formation elsewhere. The relative superimposition and the degree of pedogenesis are the major criteria used to distinguish older component members from younger ones. The distribution of the members has been mapped in detail in a number of type areas, but elsewhere the identification of individual members is less certain. The component members tend to form distinctive layers under east-



Component Members of Upper Pleistocene Woorinen Formation (Qdw)

1 Kyalite Member

2 Speewa Member

3 Bymue Member

4 Miralie Member (formerly Tooleybuc)

Carbonate in form of calcareous palaeosols, soft fine earth, glaebules, brecciated hard pans, calcareous tap root and filamental rhizoliths; overprinting and reworking by deflation common

Fig. 134. Schematic west–east and south–north cross-section of Woorinen duneforms, showing stratigraphic relationships between Kyalite, Speewa, Bymue and Miralie Members of Woorinen Formation, in type area at Woorinen Settlement (SWAN HILL – after soil stratigraphic units of Churchward, 1960, and modified terminology of Lawrence, 1966).

ern and southern dune slopes, whereas under northern and western slopes, the lime-rich pedogenic horizons tend to merge to form extensive areas of calcrete rubble (Fig. 134). A number of additional older soil horizons are known to underlie the oldest defined member, but the lateral extent and preservation of these units is largely unknown.

Unit: Unnamed Quaternary aeolian sand plain unit
Age: Quaternary, mainly Late Pleistocene to Holocene
Map symbol: Qdp

Lithology. Qdp is dominated by unconsolidated red or brown clayey siliceous sand, with clay pellet aggregates and admixed with loamy soils. The sand component consists of medium to fine-grained quartz with red clay cutans. Qdp has been modified by pedogenesis, and includes iron and carbonate-cemented nodules grading to calcrete hardpans. Near the northwestern margins of the basin, Qdp ranges in lithology from silty sand to sandy silt (Rogers, 1978). In some areas, such as those adjacent to the Darling River and Darling Anabranch lakes, the unit has a high proportion of clay pellets and a high salt content.

Distribution and thickness. Qdp is a morphostratigraphic unit which forms sand plains over extensive areas in the northern Murray Basin, between the colluvial footslopes (Pooraka Formation) and dune systems of the Woorinen Formation. Qdp also covers some areas near the eastern margin, and includes narrow sand plains adjacent to fluvial systems. The distribution of Qdp is shown in Figure 130; it is a thin unit, with a maximum thickness of a few metres. Morphostratigraphic equivalents of the unit also occur in a transitional zone between the Wimmera and Mallee landscapes in southern areas of the basin in Victoria. These were included in the Woorinen Formation by Lawrence (1975).

Topography and vegetation. Qdp forms extensive, flat to gently undulating plains; drainage is internal, and numerous fluvio-lacustrine depressions occur locally within the plains. The unit also forms narrow aeolian-modified sand plains adjacent to rivers and lakes. The Qdp plains are generally sparsely vegetated, with low shrubs, saltbush, and a few low trees dominating the flora. Saltbush is particularly characteristic of areas 'down-wind' from the large ephemeral lake complexes adjacent to the Darling Anabranch and Darling River.

Characteristics. Qdp is a composite morphostratigraphic unit, and is characterised by geomorphic expression and lithology. It is readily distinguished from the dunefields of other aeolian units by geomorphic expression, and is distinguished from the fluvial plains of Shepparton Formation by lithol-

ogy.

Environment of deposition. The Qdp sand plains were deposited in mainly aeolian environments. In the west, the plains have been modified by pedogenesis, and locally further modified by internal drainage development. The Qdp plains which have been mapped adjacent to fluvial systems consist of aeolian-modified sediment derived partly from adjacent lakes and rivers. In the region of the Darling Anabranch lakes, for example, the unit includes fluvial and lacustrine sediments which have been strongly modified by aeolian processes and admixed with saline clays deflated from lake floors. The sediment provenance of some of the extensive sand plains in the northwest is less certain, but the deflated Pliocene Sands in the west (Loxton–Parilla Sands), as well as periodically remobilised finer-grained components derived from the Woorinen Formation seem likely sources.

Stratigraphic nomenclature. Rose (1967) described a unit similar to Qdp on the MENINDEE legend, although he incorporated some coarser-grained sediments which we have included in Qfr (Pooraka Formation) on the enclosed 1:1 000 000 geological map. Similarly, Bryan (1966, 1968) described 'flat to gently undulating plains of red and brown clayey sand, loam and lateritic soils' on both MANARA and IVANHOE; much of this unit has been included in Qdp. Bowler & Magee (1978) described an undulating 'sand plain', comprising 'hummocks' of sand and sandy clay, from the Mallee region; this is also included in Qdp. The Qdp sand plains were informally described by Brown & Stephenson (1985, 1986). A formal type area has not been selected, as Qdp has highly variable ages and stratigraphic relationships. In CHOWILLA, Rogers (1978) mapped a transitional unit (which he called 'Qp') between the Pooraka Formation colluvium and the Woorinen Formation dunefields; he assigned a Late Pleistocene age to this unit, which has been incorporated into our Qdp sand plains.

Stratigraphic relationships and age evidence. Qdp is a composite unit of various ages and stratigraphic relationships. Its age ranges from Late Pleistocene to Holocene, but most Qdp sand plains probably formed after the climate of the Murray Basin became drier between about 0.7 and 0.4 Ma ago (Bowler, 1980, 1982; An Zhi–Sheng & others, 1986). Qdp plains were formed from a variety of source materials, and are generally stabilised by vegetation. The sand plains mainly consist of fossil Pleistocene landscapes, which were active during past periods of aridity. At the present-day, adjacent to fluvio-lacustrine systems, and in over-grazed areas, they are locally active during periods of drought.

In the north and west, Qdp may overlie a number of older stratigraphic units, as well as basement near the basin margins. The former include Pliocene sand (Loxton–Parilla Sands), Blanchetown Clay, and Shepparton Formation. Qdp interfingers with and is overlain by Pooraka Formation near the ranges, and is overlain by the fluvial deposits of intermittent streams (Qa); it also commonly develops calcrete profiles. The Qdp plains adjacent to modern Darling and Darling Anabranch fluvial systems are partly sourced by deflation of the adjacent large lake systems and are therefore characterised by high clay, gypsum and salt contents. The Qdp sand plains in the eastern Murray Basin possibly have different stratigraphic origins, and were probably formed from Pleistocene dune and fluvial sands, rather than from the Loxton–Parilla Sands, as these are found only in the west of the basin.

Data sources. For information on Qdp sand plains, see Rose (1966), Bryan (1966, 1968), Bowler & Magee (1978), Rogers (1978), and Brown & Stephenson (1985, 1986).

Unit: Undifferentiated Quaternary lacustrine-derived aeolian lunette deposits (crescentic transverse dunes)

Age: Quaternary, mainly Late Pleistocene, with some reworked Holocene components

Map symbol: Qdl

Component units: Lake Victoria Sand, Dunedin Park Sand Member, Nulla Sand Member, Talgarry Sand Member, Golgol unit, Mungo unit, Zanci unit, Kow Sand, Buntigoola unit, Kinchega unit, Packer unit, Tandou unit, Bootingee unit (Table 36)

Associated units: Undifferentiated Quaternary lacustrine deposits (Ql); saline lake deposits of Yamba Formation (Qly)

Remarks. The lunettes (crescentic transverse dunes), which occur adjacent to the down-wind margins of many of the lake systems of the Murray Basin form a morphologically distinct, but lithologically variable, unit. The unit has been examined in detail at various localities, and individual lunettes have been subdivided into a number of separately named stratigraphic intervals. The character of these stratigraphic intervals varies from one locality to another depending on the palaeohydrologic history of the adjacent lake system. Those which have been investigated in detail serve as type examples, and

lunette
C
D
Lake Mungo
Chibnalwood
Lunette
A
B
N
138°
141°
144°
147°
32°
34°
36°
SA
NSW
SOUTHERN OCEAN
VIC
0
5 km

have been used to interpret past variations in palaeoclimatic and palaeohydrologic conditions. The major lunettes which have been described in the literature are listed in Table 36.

Lithology. Many of the lunettes in the Murray Basin are composite bodies, with a number of superimposed beds of dissimilar lithologies, each deposited during a separate phase of aeolian accretion. They consist of various permutations of well-sorted, brown, red and grey siliceous sand, silty clay, clay pellet aggregates, gypseous clay pellets, and pale grey to white gypsite. Sand within the unit is poorly consolidated, but older components, particularly in clay-dominated lunettes, have been increasingly modified by pedogenesis, and include intercalated red calcareous and gypseous palaeosols with calcrete glaebules and rhizoliths. In places, the lunettes are capped by mobile dunes of well-sorted yellow quartz sand.

Clay lunettes and clay layers within composite lunettes consist mainly of sub-rounded to elongated pelletal clay aggregates, usually with silt and fine-grained quartz or carbonate grains. The clay pellets are commonly associated with similar-sized quartz sand grains. In places, former clay pellets are now disaggregated. Most lunettes have been subject to deflation and erosional gullying, resulting in the exposure of superimposed layers (Figs 137, 139; see also Fig. 166). Some lunettes, associated with surface-water dominated lakes, consist almost entirely of quartz sand (e.g. Barmah sand hills adjacent to former Lake Kanyapella – Bowler & Harford, 1966a,b; Bowler, 1978a). Sand-dominated lunettes are particularly well-developed on the northeast side of lake basins, such as Lake Hindmarsh, Lake Albacutya and Lake Garnpung, which have long histories of surface-water domination (Bowler, 1983). The very large lunette flanking Lake Victoria also has a high proportion of fine-grained sand (Gill, 1973a). Others, such as the massive clay dune of the Chibnalwood lunette (Fig. 135; Dare-Edwards, 1982) have a pelletal clay content of 80%, whereas in the multi-layered sand and gypsum clay pellet lunette at nearby Lake Mungo (Fig. 135) Bowler (1983) noted less than 50% clay content. Much of the crestal Mungo lunette consists of a modern deflation residue of clean white sand (high reflectance area on Fig. 135), which is largely absent from the Chibnalwood lunette. Other lunettes, associated with groundwater discharge lakes within the Mallee, consist almost entirely of impure gypsite and gypsum clay pellets. These form topographically subdued and deflated lunettes, and are associated with both fossil and active groundwater-dominated lake complexes. On RENMARK, Firman (1972) differentiated many of the gypsite lunettes as a sub-division of the Yamba Formation, as did Rogers (1978) on CHOWILLA. Similarly, on the enclosed geological map many areas shown as Yamba Formation are a composite of lake floor and deflated lunette deposits.

The most comprehensively studied lunette is at the 'Walls of China' at the eastern margin of Lake Mungo (Fig. 135; Bowler, 1971, 1973, 1976a, 1978b). The Mungo lunette incorporates a series of superimposed units, each characterised by distinctive lithologies and separated by palaeosols (Fig. 137). Deflation and gullying have exposed the units on the western slopes of the lunette. At the base of the succession, and forming the core of the lunette, the Golgol unit consists of red quartz sand under a mature dark-red calcareous soil with hard calcareous nodules and concretions (Fig. 138). Towards the base of the eroded western slope of the lunette, the overlying lower Mungo unit comprises well-sorted beach sand with high-angle cross-bedding and freshwater shell debris, entrenched into an eroded GolGol surface. Farther up the lunette (to the east), the lower Mungo unit is formed of red to reddish-yellow quartz sand under a dark humic calcareous soil (Middle Mungo Soil), further overlain by up to 5 m of sub-horizontally bedded greenish-grey clayey sand with clay pellet aggregates overlain by palaeosols (upper Mungo unit). The Mungo unit is overlain by grey finely laminated pelletal clay of the Zanci unit, under a brown to red-brown calcareous earthy soil. Modern dunes of mobile wind-rippled residual sand form the uppermost unit of the Mungo lunette, extending along the deflated crest and blanketing the leeward slopes. The wind-winnowed sand is only poorly stabilised by shrubs and grasses, and is eroded to form deflation hollows in crestal areas (Fig. 139). It locally forms small but high and steep-sided blowout dunefields, which are currently avalanching away from the deflated eastern margin

Fig. 135. Airphotomosaic showing lunettes of Lake Mungo and Chibnalwood Lakes (POONCARIE); Mungo lunette is a composite of clay-pellet and sand-dominated layers, whereas Chibnalwood lunette consists predominantly of clay. Sections A–B and C–D are shown on Fig. 137; mosaic consists of photos from National Mapping RC9 Series, Pooncarie Run 6, Nos. 91, 93, and Run 7, Nos. 149, 151; photographed 17/11/1964.

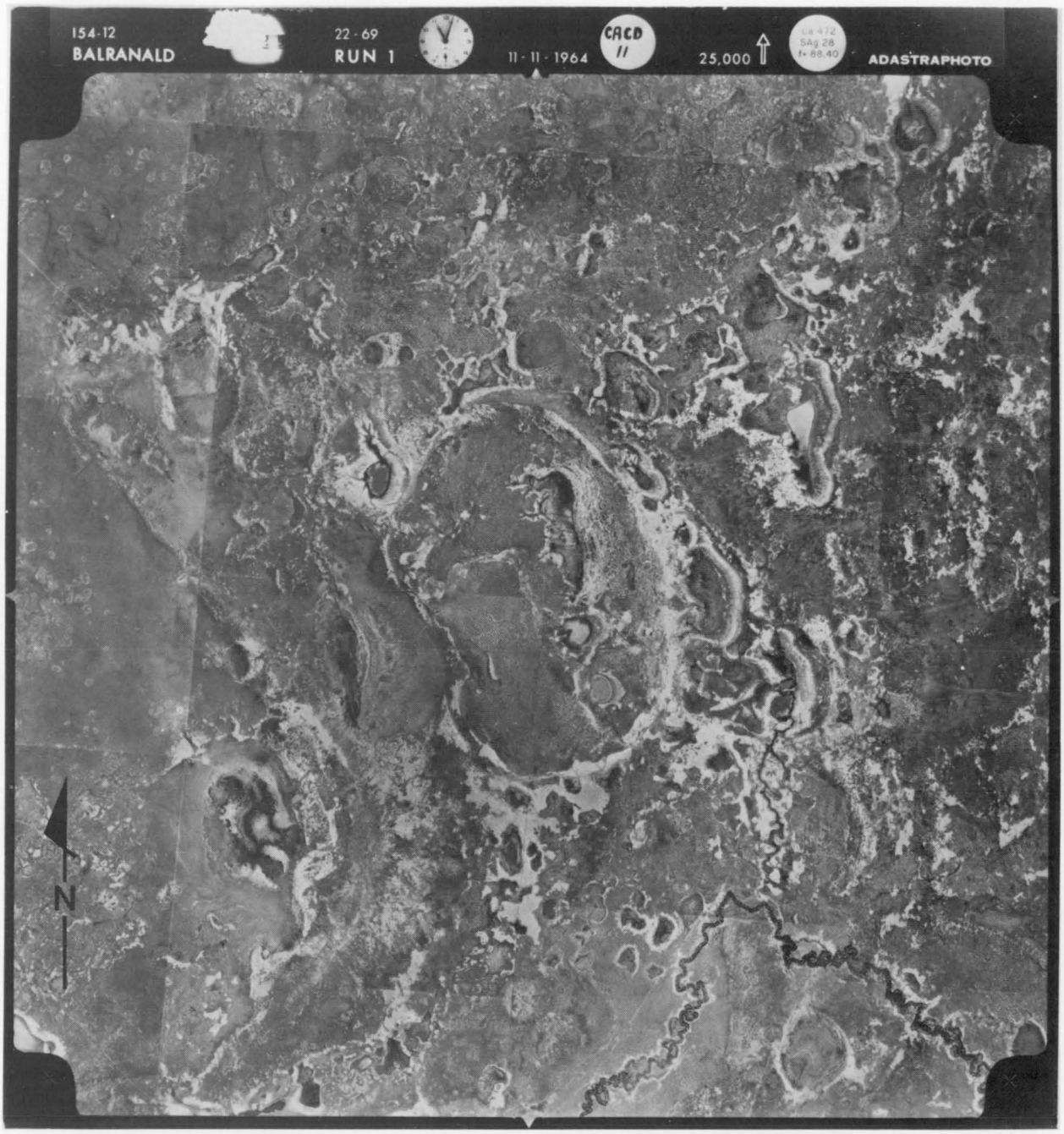


Fig. 136. Airphoto showing deflated gypsum clay-pellet lunettes, inactive groundwater-discharge lake systems, and scalded texture of the northern Hatfield complex, north of Balranald. Photo from National Mapping RC9 Series, Balranald Run 1, No. 29; photographed 11/11/1964.

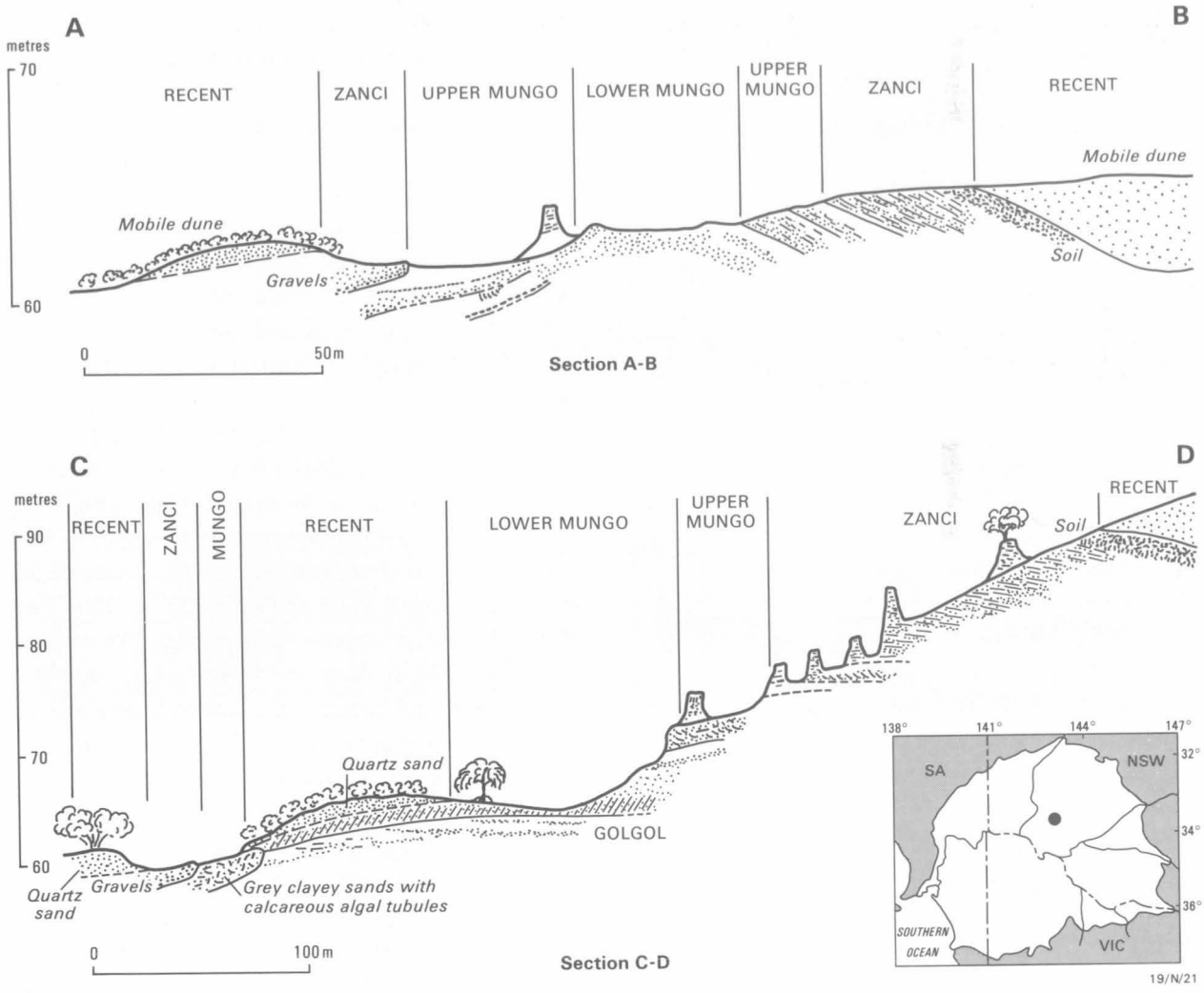


Fig. 137. Cross-sections through Lake Mungo lunette – described in publications on the Willandra Lakes by Bowler (1971, 1973, 1976b, 1978b); sections from Bowler (*in* Magee & Beaton, 1985) and Bowler (*in* Magee, 1986). Location of sections shown on Figure 135.

of the lunette. These consist of residual, extremely well-sorted clean white quartz sand. Fine-grained sediments (including clay and salt components) winnowed from the deflated lunette form a thin blanket deposit within soil profiles over extensive areas down-wind of the lunette.

Distribution and thickness. Lunettes are widely distributed throughout the basin (see Fig. 143), but are particularly well-developed in the more arid areas of the western Riverine Plain (Fig. 136) and the adjacent Mallee landscape. Major topographically prominent lunette systems are associated with the lakes of the Darling River in the Menindee region (see Fig. 142), and with the lakes of the Darling Anabranch system farther south (Figs 140, 141). Large lunettes are also associated with the terminal lake systems of the Willandra Creek (Fig. 142), the Wimmera River, and Lake Tyrrell (see Fig. 147). Topographically subdued but equally extensive lunettes occur throughout the western Riverine Plain, and are particularly well-developed in the lower Murrumbidgee area, and west of the Lachlan River at the northwestern margin of the Riverine Plain (Fig. 136; see also Fig. 150). In the east, extensive but topographically subdued lunettes have developed at localities, such as near Barmah 20 km northeast of Echuca on BENDIGO, and to the east of Lake Urana on JERILDERIE. Numerous subdued and eroded remnants of lunettes also occur within the aeolian dunefields of the western Murray Basin. Many of these are located within or adjacent to gypsite flats and irregularly shaped playa lake complexes, whereas others are developed on terminal lake complexes. The thickness of lunette deposits ranges from a few metres to 40 m in some of the larger bodies.

Outcrop and geomorphic expression. Lunettes are crescentic, concave to the west, transverse dunes

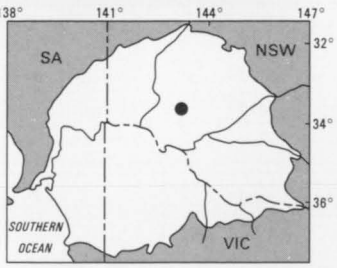


Fig. 138. Palaeosoil at top of Golgol unit towards base of lunette at Lake Mungo (POONCARIE).

A mature dark red calcareous soil, with hard calcareous concretionary nodules and veinlets.

which developed on the eastern side of lake basins. In plan view, the crescentic horns of the lunettes face into the prevailing winds. In places, they form large single bodies, but elsewhere topographically prominent lunettes are nested within flanking, progressively older and topographically subdued lunettes. In the Willandra Lakes system, for example, multiply laterally displaced lunettes flank the Chibnalwood Lakes, which developed within the floor of former Lake Arumpo, which is itself further flanked to the east by a major lunette (Fig. 135). Similarly, many of the large ephemeral lakes of the Darling River and Darling Anabranch, such as Travellers Lake, are flanked to the east by at least two major lunettes, in addition to a number of older topographically subdued lunettes.

The orientation of the large lunette flanking Lake Popiltah on the Darling Anabranch is typical of many lunettes found elsewhere in the Murray Basin (Fig. 140). These are always located at the eastern or northeastern margins of the lake basins. Bowler (1983) noted that the sand-dominated lunettes are characterised by a symmetry about a northeasterly oriented axis, whereas the clay-dominated lunettes are characterised by an east–west axis of symmetry. He suggested that the fixed orientation of lake shore beaches, providing the sand to the sand-dominated lunettes, was controlled by the prevailing wind direction (which in turn controlled lake circulation and wave patterns), whereas the orientation of clay-dominated lunettes reflects seasonal variations in the direction of the winds providing clay pellet material from deflated lake floors. Lunettes which consist largely of clay material tend to form low-lying features with smooth but gullied surfaces, whereas mixed and sand-dominated lunettes are frequently irregular in topography, with a hummocky surface characterised by deflation hollows. Gypseous clay dunes are usually broad, with low crests and low-angle slopes, and are characteristically vegetated by clumps of low samphire shrubs.

The multiple layèred Popiltah lunette forms a 1 km wide curvilinear ridge extending for 22 km, with an elevation of up to 76 m.a.s.l. (Fig. 140). This elevation is some 40 m higher than the adjacent lake floor to the west. The crescentic configuration of the lunette is oriented in an arc from 335° to 160° East of North, and is concave to the west. An arcuate swale, some 30 m deep and 200 m wide, separates this youngest and largest main lunette from a slightly older and topographically subdued lunette with an elevation of up to 60 m.a.s.l. Remnant traces of a number of older lunettes, partly buried beneath a veneer of sand, silt, and gypsiferous clay (included in Qdp/Qdw on enclosed map) are discernable over a zone extending at least 5 km to the east of the lake. Similarly, Travellers Lake is flanked to the east by a particularly well-defined lunette complex up to 8 km wide, which is in turn flanked by a zone of subdued lunette features extending several kilometres farther east (Fig. 141). At present, many of these down-wind areas are blanketed by soils with high silt, clay, and gypsum contents, derived from material winnowed from the dry lake floor and deflated lunette to the west. These down-wind soils also have high chloride levels (Macumber, 1968, 1970). East of the Darling Anabranch, for example, the amount of salt is reflected in the replacement of the regional Mallee vegetation by a blue-bush assemblage in areas down-wind from deflated lakes and lunettes.

The composite nature of many of the larger lunettes is revealed where accretionary layers have been exposed in erosional rills and gullies, which have deeply dissected the weakly consolidated components. The younger accretionary layers have been subjected to persistent erosion by strong wind action to form amphitheatre-like deflation hollows (Fig. 139). These are largely devoid of vegetation apart from remnant pinnacles; the latter are up to 4 m in height, and are remarkably well-protected from erosion by a resilient mantle of vegetation. White, pale-yellow, well-sorted and clean quartz

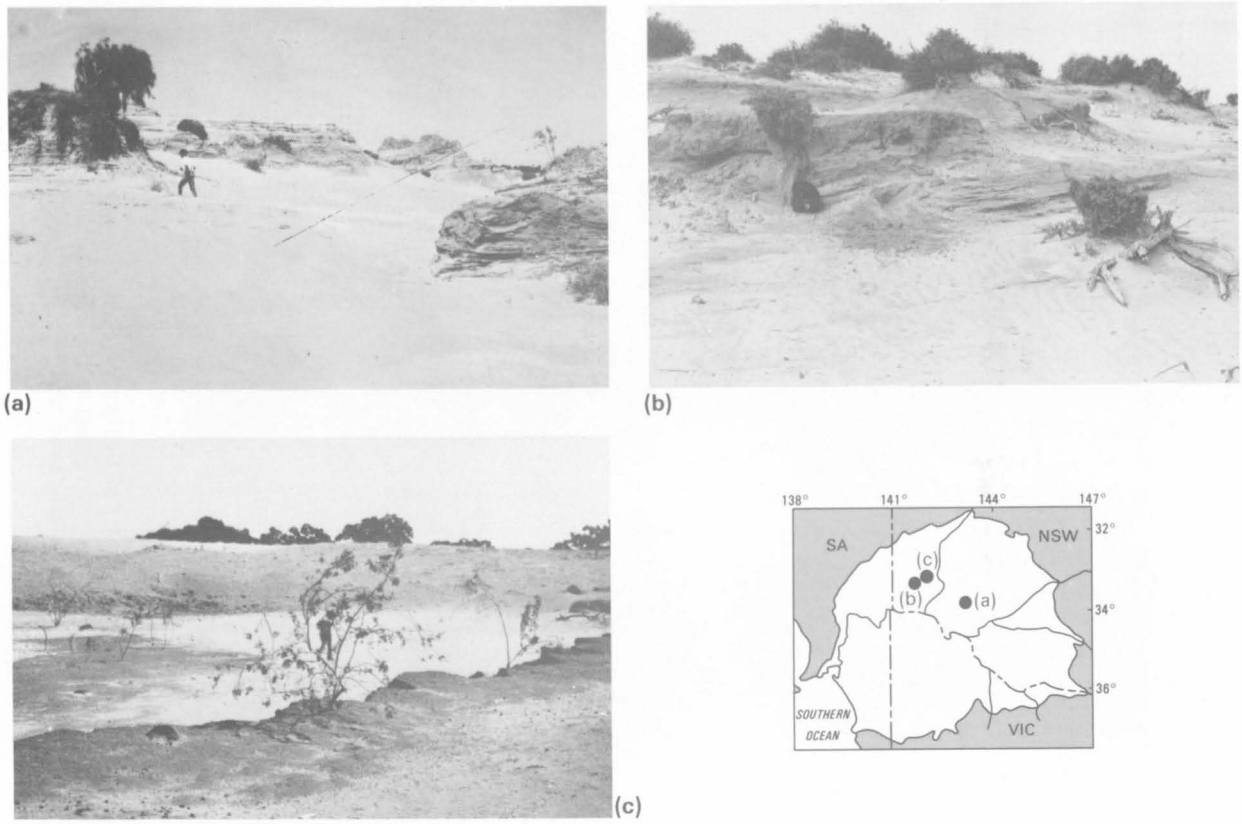


Fig. 139. (a) Eroded lunette at Lake Mungo (POONCARIE). (b) Clay pellet beds capped by weakly developed soil, exposed in eroded lunette at Yelta Lake (ANABRANCH). (c) Deflation hollow within eroded lunette at Travellers Lake (ANABRANCH).

sand derived from the deflation hollows is currently accumulating in dunes adjacent to the crestal regions and down-wind slopes of the lunettes. At localities, such as the northern end of Lake Albacutya and the eastern margins of Lake Mungo, such dunes now form irregular easterly migrating blow-out dunefields. As a consequence of this deflation, residual materials heavier than sand particles have accumulated within the deflation hollows. Commonly-found items include aboriginal artifacts, fireplace stones, middens, shells, and marsupial remains representing the concentrated residue of deflationary erosion of several layers within the lunette succession.

Internal geometry. Sand-dominated lunettes are characterised by steep down-wind slip faces on the eastern margins of dunes, whereas the clay-dominated lunettes are characterised by high asymmetry with long gentle down-wind slopes and shorter steeper windward slopes (Bowler, 1983). Bedding is not well preserved within the clay dunes, but remnant bedding traces are usually finely laminated and of low angle with slopes of less than 15°. In contrast, steeper bedding traces within the sand lunettes reflect slip-face avalanching of sand, which has been piled into unstable dunes by saltation. The sand dunes are frequently characterised by high-angle bedding and truncation of less-steeply dipping windward slope deposits.

Palaeontology. The lunettes provide some of the best-preserved Quaternary faunas in the Murray Basin. In particular, their fossil assemblages provide a record of past environmental conditions in the adjacent lake systems and also of human activity in the region. The vertebrate fossils of the lunette flanking Lake Menindee were described by Tedford (1955, 1967), at Lake Tandou by Merrilees (1973), Lake Victoria by Marshall (1973), the Willandra Lakes by McIntyre & Hope (1978), and Lake Cawndilla by Aplin & others (1981). Additional sites at other lunettes in the Darling region are listed in Hope & Jacobs (1982). At Lake Victoria, Marshall (1973) described an abundant and diverse fauna with extinct giant marsupials, as well as the megafaunal ancestors of modern dwarfed marsupials.

Several authors have speculated on a possible correlation between the extinction of the giant marsupials and the arrival of aboriginal man (Jones, 1968; Merrilees, 1968; Hope, 1978). At Lake Menin-

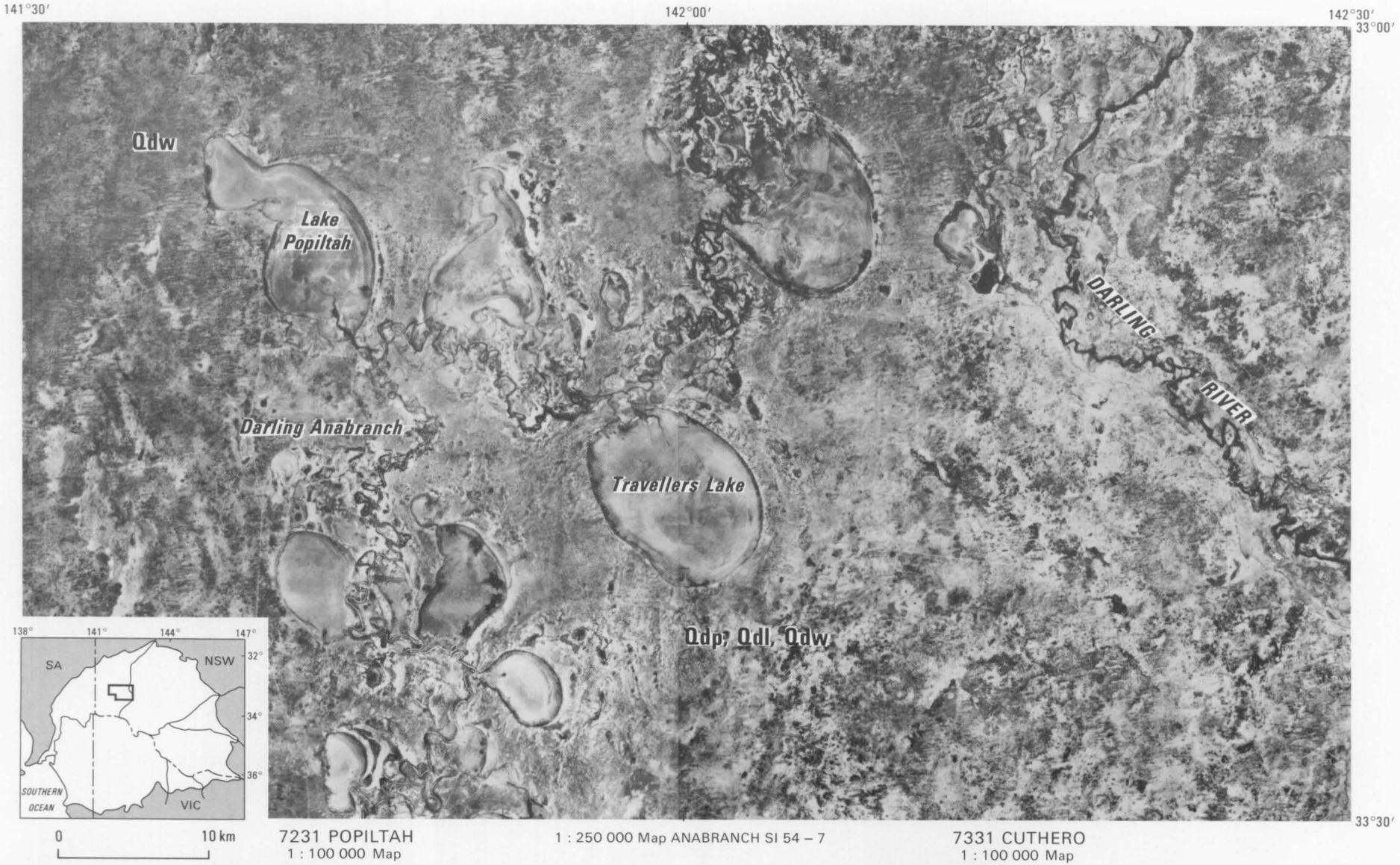


Fig. 140 Photomosaic of Popiltah and Cuthero 1:100 000 Sheet areas, showing lakes (Ql) and associated lunettes (Qdl) of part of Darling Anabranch system, entrenched within aeolian landscape of northwestern Murray Basin. Dunefields west of Anabranch lakes consist of Woorinen Formation (Qdw), with minor saline lake deposits (Qly). Area between Anabranch lakes and Darling River consists of complex intercalations of deflated lunette deposits (Qdl), 'sand plains' (Qdp), and dunes of Qdw – all with a high content of lacustrine-derived aeolian-deposited salts.

dee, Tedford (1967) identified the charred metatarsal of an extinct giant Kangaroo *Macropus ferragus* in an aboriginal fireplace dated at 26 300 ± 1500 yrs. B.P. Marshall (1973), however, implied that the fossil may be of *Macropus titan*, which is an ancestor of a dwarfed modern kangaroo. At Lake Victoria he found that the large Pleistocene fauna pre-dated 18 000 yrs. B.P., but found no direct evidence of an association between aboriginal man and extinct – as opposed to dwarfed – giant marsupials.

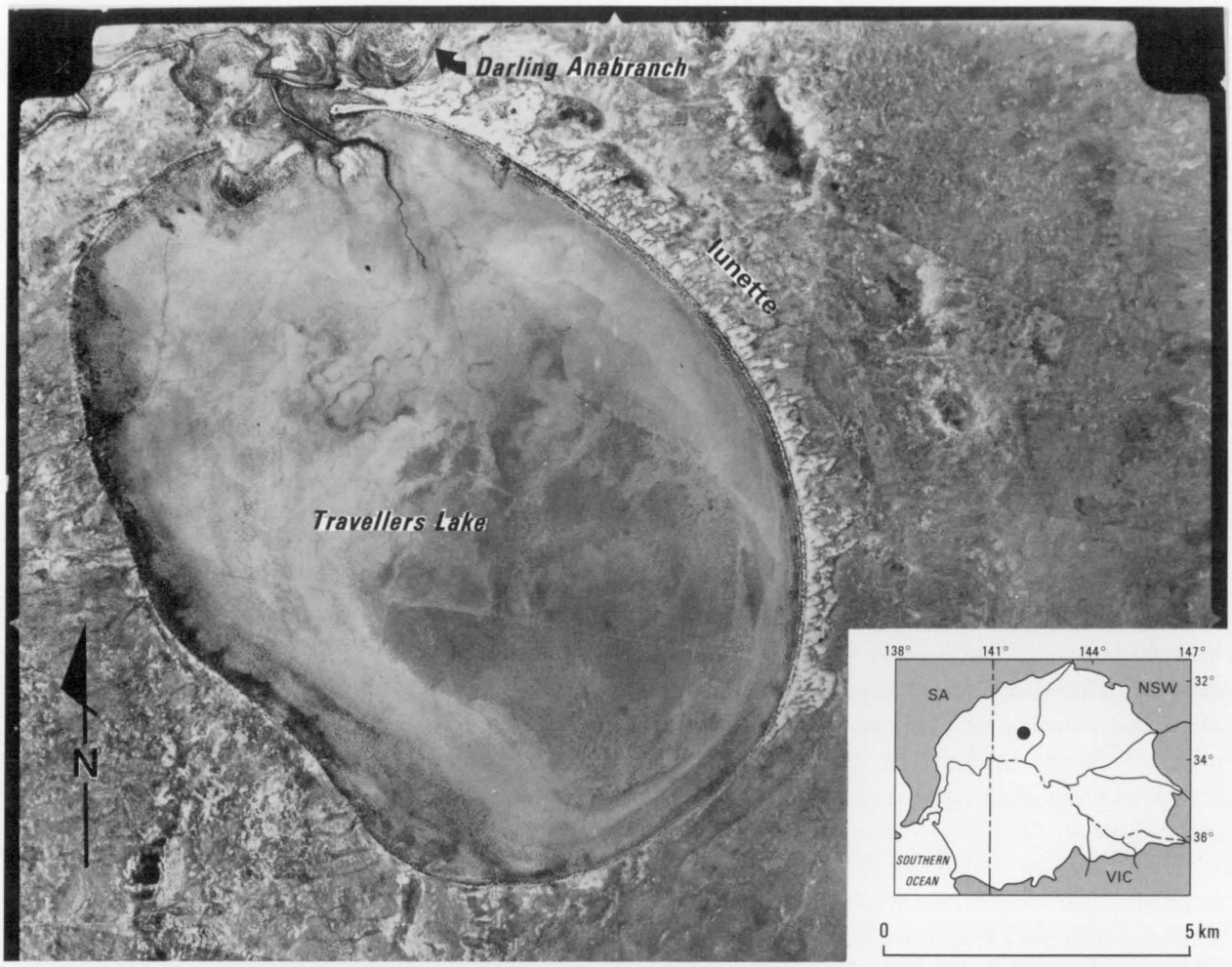
In the Lake Mungo lunette, Bowler & others (1970, 1972), and Thorne (1971) discovered some of the oldest human remains in Australia, including a cremated woman at a site dated at 26 000 yrs. B.P., and an aboriginal man at a site dated at 30 000 yrs. B.P. The oldest dated sites are at least 32 000 yrs. old (Allen, 1972; Barbetti & Allen, 1972), and human habitation is thought to extend back to at least 40 000 yrs. (Mulvaney & Golson, 1971). The deflation hollows within the larger lunettes preserve the sifted remains of aboriginal hearths, artifacts made of silcrete or ferricrete, as well as the discarded remains of charred mussel shells, marsupial and fish bones.

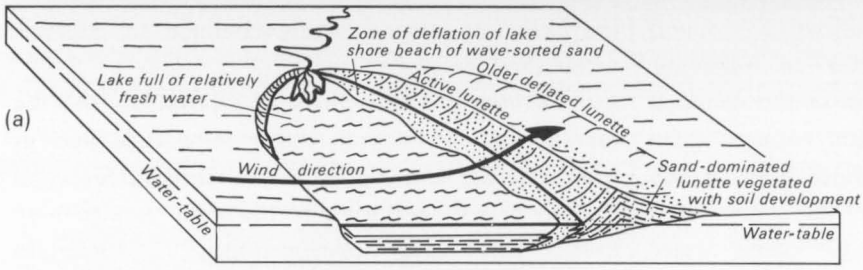
The lunettes contain fragmented, wind-blown, lacustrine shell fragments, as well as larger mussel shells and fish bone fragments, dumped in aboriginal middens. The mussels have mainly been identified as *Velesunio ambiguus*, a large unionid which is found mainly in fresh to brackish water environments. These shells are preserved mainly in sand-dominated lunettes or layers, and are thought to have been present during periods of high water levels within relatively freshwater lakes. Many of the comminuted shell fragments are of the small inland water gastropod *Coxiella*, which can survive in relatively high salinity waters (30 000 to 50 000 mg/litre), and is found in clay lunettes and in gypsiferous clay layers within composite sand/clay lunettes. Additional water-derived macrofossils include the gastropods *Lympaea tomentosa* and *Bulinus* (*Isadorella*) *necombi*, as well as the small lamellibranch *Corbiculina* and/or *Sphaerium sp* (Bowler, 1983). The shells of small land snails *Pupoides* (*Themapupa*) *adelaidae* or *beltiana* have also been identified.

Age evidence. Aeolian landforms of the Murray Basin initially developed after cessation of deposition of the underlying Blanchetown Clay following the drying of Lake Bungunnia between 0.4–0.7 Ma. Some of the older lunette components may date from this period. Most of the preserved components of the lunettes are essentially fossil features dating back to at least the last glacial maximum period. The modern white sand dunes are erosional products clearly forming at the present day. Radiocarbon dates from a variety of lunettes indicate that, the youngest accretionary layers appear to have formed between 18 500 and 16 000 yrs. BP (Lake Albacutya – Gill, 1971; Lake Victoria – Gill, 1973a; Willandra Lakes – Bowler, 1976a). At Lake Mungo, for example, the Zanci unit has been dated at 16 000 to 18 000 yrs. BP. Dates from a palaeosol from the middle Mungo unit are around 35 000 yrs. BP., and from the upper part of the Mungo unit are around 32 000 to 34 000 yrs. BP. Dates from the base of the Mungo unit are beyond the upper limits of the C^{14} method, but indicate an age in excess of 40 000 yrs. BP. The underlying Gol Gol unit may be significantly older.

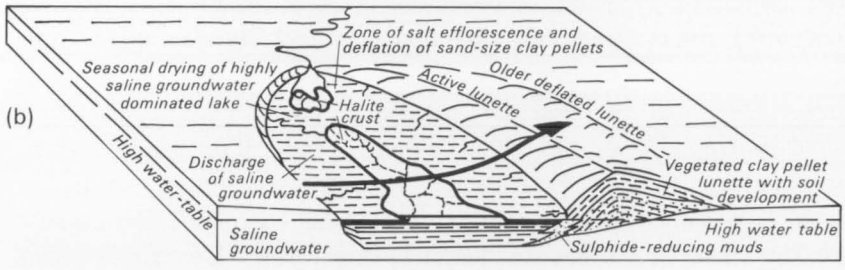
Characteristics. The lunettes of the Murray Basin form a morphostratigraphic unit (Qdl), identified mainly by the characteristic crescentic transverse dune morphology of its components. Lithology is not the principal criterion, although the dunes consist of a restricted range of possible lithologies. The detailed lithology can vary from one lunette to another, reflecting variations in local palaeohydrologic controls. With the exception of a few currently active systems, and residual dunes associated with modern deflation, the lunettes are eroded fossil features. Major phases of accretion appear to have been largely synchronous throughout the basin, and were largely confined to intervals within the Late Pleistocene.

Interpretation of environment of deposition. All the lunettes of the Murray Basin were deposited as transverse aeolian dunes under the influence of easterly or northeasterly directed wind regimes in an arid or semi-arid environment (Hills, 1939, 1940a). In detail, however, the range of lithofacies – forming both individual dunes and accretionary layers within composite dunes – reflects a complex array of depositional processes which have operated at various times during the period of formation of lunettes. Few lunettes are actively accreting sediment at present. Most are fossil Upper Pleistocene–Holocene features, and were last active when palaeohydrologic conditions were subtly wetter (sand-dominated lunettes) or drier (clay-pellet dominated lunettes) than those of the present. As discussed below, sand-dominated phases are thought to be the products of deflation of lake beach deposits formed by wave-action adjacent to 'deep', relatively fresh, surface-water dominated lakes, during periods of wetter climates. Clay-pellet dominated lunettes are thought to be the products of periods transitional between wetter and drier climates, such as at the onset

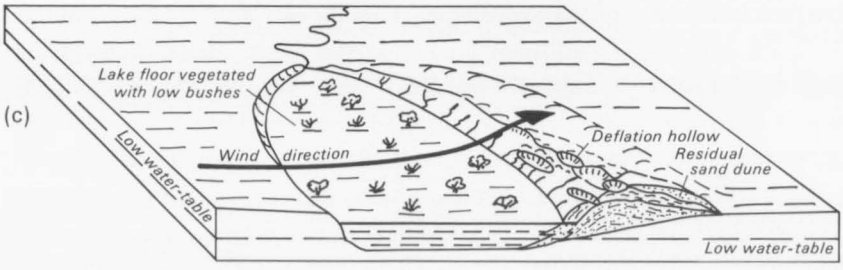




(a) Formation of sand-dominated lunette by saltation of sand grains from deflated lake shore beach adjacent to relatively full, surface-water dominated, freshwater lake; winds from W and WSW resulted in wave-sorting of sediment to form lake shore beach to E and ENE; lunettes thought to have been vegetated with development of soil profile; relatively freshwater conditions indicated by shell debris and fishbones, as well as by indications of aboriginal settlement.



(b) Formation of clay pellet-dominated lunette by saltation of sand-size clay pellets from deflated lake floor, during periods of seasonal aridity and drying of groundwater-dominated saline lake, resulting from discharge of highly saline groundwater from high water-tables; suitable conditions thought to have prevailed during transitional periods when climatic conditions were increasingly hot and arid but when high groundwater tables were inherited from a preceeding less arid climatic phase.



(c) Formation of residual sand dunes deposited over eroded and deflated lunette; deflated clay and salt components of lunette reworked and deposited down-wind, while residual sand deposited as dunefields of clean white sand over crestal and eastern slopes of lunette, as well as adjacent to deflation hollows on western slopes; lunette subject to wind erosion to form extensive deflated amphitheatre-like hollows devoid of vegetation and containing remnant pinnacles of vegetated lunette; also eroded by heavy rains from infrequent thunderstorms to form deep vertical rills and gullies; groundwater-tables too low to allow discharge of saline waters, and lake floor sediments partly vegetated.

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of glacial aridity, when saline groundwater tables were high, but surface runoff was low, and saline groundwater-dominated lake waters were seasonally evaporated (see also 'Yamba Formation' and 'Tyrrell beds').

Harris (1939) and Stephens & Crocker (1946) suggested that the lunettes formed by deflation of dry lake floors during arid phases. In contrast, Hills (1939) noted that the nested lunettes in the Benjeroop area near Kerang (SWAN HILL) appeared to be related to successively lower lake levels, and proposed that clay dunes originated by the flocculation of clay material by salt spray from lakes with water. Bowler & Harford (1966a,b) and Bowler (1968, 1978a) subsequently suggested that quartz sand lunettes, such as those flanking Lake Kanyapella, northeast of Echuca, were deposited by deflation of high-energy lakeshore beach sands, during extended periods of high water level within the lake. Within the lake floor of the now dry Lake Kanyapella, the presence of well-sorted beach sands with increasing grain size towards the lake basin margins (Bowler, 1980) supports this argument. These may have been reworked and winnowed during seasons with sufficiently strong winds. Campbell (1968) proposed a similar origin for clay lunettes, but Bowler (1968) and Bowler & Wasson (1984) believe that the clays of lunettes were deposited by deflation of partially exposed lake floors, during transitional wet-to-arid phases of lowered lake water levels (i.e. periods of surface aridity in combination with high groundwater tables). The mechanism involved the seasonal lowering of the groundwater table below the lake floor, by evaporation, accompanied by the development of sand-sized pelletal clay aggregates, formed by the breakdown of a desiccated lake-floor crust. The clay pellets were created by the efflorescence of fine evaporative salts, by breakdown of domal blisters and desiccated algal mats, as well as by the curling up of the laminated edges of sun-cracked desiccation polygons and pressure ridges.

At present, the sedimentological conditions referred to above operate at only a limited number of sites, and only for limited periods. At Lake Tyrrell in 1982/83, for example, during a period of particularly severe drought accompanied by high velocity summer winds, Bowler (1983) observed that the main area of deflation was restricted to a zone located at the edge of the salt crust. A thin 1-2 cm thick layer of vertically growing needle halite appears to have been responsible for breakdown of the desiccated lake sediment surface layer. Similar conditions were observed at other sites in the Nulla Nulla and Scotia areas of western New South Wales (see Fig. 145, 'Yamba Formation' and 'Tyrrell beds'). Clay pellets, in the form of rippled sheets and mound-like dunes, were then deposited in the adjacent lunette, to the east of the deflation zone, by the dominant southwesterly winds. These clay pellets are thus thought to have accumulated over the lunette in a similar manner to sand grains, and to have been trapped and partly preserved from erosion by samphire vegetation. The clay dunes are thought to have rapidly stabilised, owing to cementation by salts and rapid packing and coalescence of the cohesive clay pellets.

In detail, however, the character of each lunette is controlled by the interplay of factors such as relative surface water and groundwater inputs to the associated lake system, as wel as climatic conditions, both at the lunette site and in the catchments of associated river systems. Development of the lunettes of the Willandra system, for example, has been partly influenced by climatic conditions in the southeastern highlands, whereas those of the Darling Anabranch reflect climatic events (in the form of surface water input) in southeastern Queensland.

Macumber (1970) and Bowler (1983) indicated that the production of clay pellets requires that the groundwater tables are sufficiently high to allow seasonal discharge of saline waters to the lake system, but at a sufficiently low level to allow seasonal evaporation rates to exceed rates of groundwater discharge, resulting in seasonal desiccation and salt efflorescence. The formation of clay pellet-dominated lunettes was thus associated with deflation of lake floors by dry, summer winds, probably originating in the continental interior. As discussed by Bowler & Wasson (1984), this process may have been particularly active during periods transitional between wet and dry climatic phases, when inherited high groundwater tables may have coexisted with seasonally arid conditions. Major periods of lunette accretion possibly, therefore, ac-

Fig. 141. Airphoto of Travellers Lake and lunette adjacent to Darling Anabranch; photo from National Mapping RC9 Series, Anabranch Run 3, No. 214; photographed 15/10/1968; see accompanying text and Bowler (1983), Bowler & Wasson (1984) for descriptions of mechanisms thought to have resulted in formation of various sand and clay-pellet dominated layers within lunettes.

Fig. 142. LANDSAT scene of northern Murray Basin, showing Menindee, Darling Anabranch and Willandra Lakes systems, and Darling River, entrenched within aeolian landscapes.

companied the onset of periods of glacial aridity as envisaged by Galloway (1965).

In summary, lunettes composed of quartz sand, and the quartz sand layers within composite lunettes, are thought to have been deposited when lake systems were filled with water. These dunes are thought to have grown by saltation transport of sand grains up gentle windward slopes to a steep down-wind avalanche slope. The sand dunes were relatively unstable, locally mobile, and subject to reworking. In contrast, those lunettes, and layers of composite lunettes, which consist largely of clay or gypsum are thought to have been deposited during periods of deflation of adjacent lake floors (Bowler, 1983).

TABLE 36. STRATIGRAPHIC SUB-DIVISIONS OF LUNETTE SEDIMENTS (Qdl)

Unit	*Lake System*	*Reference*	*Remarks*
Bootingee unit	Lake Tandou NSW	Hope & Jacobs (1982) Hope & others (1983)	1-8 m of pale brown sandy loam (quartz sand with small component of pelletal clay), minor calcareous & gypsiferous palaeosol (14000-27000 yrs B.P.), contains remains of fish, platypus, frogs crustaceans, deposited during high fresh lake levels
Tandou unit	Lake Tandou NSW	Hope & Jacobs (1982) Hope & others (1983)	1-3 m of red palaeosol underlain by sandy loam, loamy sand, sandy clay, calcareous & gypsiferous palaeosols, dated as older than 27000 yrs B.P. under Bootingee unit
Kinchega unit	Lake Tandou NSW	Hope & Jacobs (1982) Hope & others (1983)	1-3 m of red clays with minor thin sand lenses, contains brittle carbonate glaebules, under Packer unit
Packer unit	Lake Tandou NSW	Hope & Jacobs (1982) Hope & others (1983)	1-4 m of grey pelletal clay interbedded with sandy clay, deeply weathered soils & soft carbonate glaebules, under Tandou unit
Buntigoola unit	Lake Tandou NSW	Hope & Jacobs (1982) Hope & others (1983)	Composite unit of red colluvial sandy clay, sand lenses, grey pelletal clay, calcareous, gypsiferous soils under Kinchega unit
Lake Victoria Sand	Lake Victoria NSW	Gill (1973a)	Composite lunette of fine-grained quartz sand, sub-divided into three members
Dunedin Park Sand Member of Lake Victoria Sand	Lake Victoria NSW	Gill (1973a)	Modern sand apron derived from adjacent lake beach, includes alluvial fans washed down erosional gullies
Talgarry Sand Member of Lake Victoria Sand	Lake Victoria NSW	Gill (1973a)	Fine sand with carbonate, rhizomorphs & selenite needles, overlain by grey columnar soil, contains extant marsupials, aboriginal remains under Dunedin Park Sand Member
Nulla Nulla Sand Member of Lake Victoria Sand	Lake Victoria NSW	Gill (1973a) Marshall (1973)	Upper Pleistocene basal unit of fine sand with pelletal clay; includes a number of truncated red palaeosols, contains extinct marsupials, contains mussel shells & aboriginal middens towards top, under Talgarry Sand Member
Golgol unit	Willandra Lakes NSW	Bowler (1971, 1973, 1976b, 1978b)	Oldest named unit at Lake Mungo, consists of red quartz sand under mature dark red calcareous soil with hard nodular to massive calcrete, no sedimentary structures preserved, age unknown but older than overlying Mungo unit
Mungo unit	Willandra Lakes NSW	Bowler (1971, 1973 1976b, 1978b)	Red to red-yellow quartz sand under humic calcareous soil, under 5 m of greenish-grey silty sand with clay pellets, sand pellets, sand & clay alternations towards top, middle palaeosol dated at 35000 yrs B.P., lower Mungo older than 40000 yrs B.P.
Zanci unit	Willandra Lakes NSW	Bowler (1971, 1973 1976b, 1978b)	Youngest named unit, consists of up to 32 m of grey pelletal clays with calcareous and argillaceous silt &sand under calcareous brown to red-brown earthy soil, finely laminated sedimentary structures, well preserved
Unnamed	Barmah sand hills of Lake Kanyapella Vic. & NSW	Pels (1966) Bowler & Harford (1966) Bowler (1978a)	Well sorted, medium to fine, micaceous quartz sand (no clay content), steep foreset bedding, interpreted as being derived from lake beach during high water, windy conditions (as opposed to arid), interfingers with medium to coarse beach sand
Kow Sand	Kow Swamp Vic	Thorne & Macumber (1972) Macumber (1974, 1977)	Fine-grained, sub-rounded, well sorted, clean quartz sand with minor heavy minerals in a 4 m high lunette

These clay dunes are relatively stable. Avalanche slopes are absent and each successive layer is thought to have uniformly blanketed the previous one. The addition of successive layers is thought to have resulted in the incremental elevation and downwind migration of the crest of the lunette.

Macumber (1970) suggested that not all clay lunettes formed adjacent to desiccated lake floors, and proposed that some lunettes initially formed by deflation of 'scalded' clay pans. These pans are thought to have formed in areas where vegetation has been killed by soil salinisation due either to high groundwater tables or introduction of aeolian salts.

The locally mobile dunes of clean white sand often form the most prominent surface feature of the lunette. They appear to be the products of modern aeolian erosion and sifting. This has resulted in the concentration of sand in mobile dunes, and in the dispersal of fine-grained components over extensive downwind areas.

Stratigraphic nomenclature. The transverse dunes of the Murray Basin were first named and classified as a morphostratigraphic entity by Hills (1940a). Individually named units are listed in Table 36. Butler (1958) referred to the sediment of lunettes of the Riverine Plain as 'Colongulac dune parna', being a variant of the 'Colongulac loess' of Gill (1953).

Type areas. There is no single nominated type section, but the extensively studied lunette at Lake Mungo (POONCARIE) reveals a range of features

which are found in many other mixed layer lunettes (Fig. 137). The lunette lies within the Mungo National Park, and literature and displays explaining the geology and other aspects of the lunette are housed in the Park Information Centre. The lunette forming the Barmah sand hills (BENDIGO) is an example of a sand-dominated type, and the fossil lunettes flanking Lake Tyrrell (SWAN HILL) are representative of clay-pellet forms. The deflated lunettes flanking modern playas in the Scotia—Nulla—Pine Camp area (ANABRANCH) of southwestern New South Wales (see Fig. 143) are representative of deflated gypsite types.

Stratigraphic relationships. The unit is confined in distribution to the blanket of Upper Quaternary sediment forming the modern landscape of the basin. Similar sediment has not been identified in the subsurface. Lunette sediments are intimately related with adjacent sediments of lacustrine Yamba Formation and Ql units. Down-wind components of the unit mantle, and are also laterally intercalated with, parts of the Woorinen Formation and the Qdp unit.

Economic geology. In some areas, fossil gypsite-dominated lunettes, associated with the Yamba Formation, are of sufficiently pure quality to be mined (see 'Gypsum').

Data sources. The earliest observations and first map of the geomorphic configuration of lunettes were made by Mitchell (1839). Subsequent descriptions of particular localities and debate concerning the origins of lunettes are in Baldwin & others (1939), Harris (1939), Hills (1939, 1940a), Stephens & Crocker (1946), Smith & others (1943), Bettenay (1962), Currey, 1964, Bowler & Harford (1966a,b), Bowler (1970a,b, 1971, 1976a,b, 1978b, 1980), Campbell (1968), Macumber (1970), Gill (1971, 1973a), Stokes (1980), Dare-Edwards (1982), Magee (1986), and Hyde & Wasson (1983). Major reviews of the various types of lunettes, and of their sedimentology and genesis, with emphasis on their significance as palaeoclimatic and palaeohydrologic indicators, have been published by Bowler (1968, 1973, 1983).

Unit: Yamba Formation and other saline lake deposits

Age: Quaternary, mainly Late Pleistocene to Holocene

Map symbol: Qly

Component unit: Tyrrell beds (Table 37)

Associated units: Undifferentiated lacustrine-derived Quaternary aeolian lunette unit (Qdl); undifferentiated lacustrine deposits (Ql)

Remarks. The Yamba Formation consist essentially of an association of sediment types that were deposited in a range of local environments, in or adjacent to saline lake complexes. They include successions which reflect a seasonal interplay between aeolian, pluvial and groundwater conditions. In detail, the successions can vary from one lake setting to another. In the Murray Basin, the modern sediments of a number of saline lake complexes, such as the Raak Plains (Macumber, 1983) and Lake Tyrrell (Teller & others, 1982; Macumber, 1983; Bowler & Teller, 1986), have been studied in detail. At Lake Tyrrell (Fig. 147), Teller & others (1982) and Bowler & Teller (1986) referred to the lacustrine facies as the 'Tyrrell beds' (Table 37).

Lithology. Exposures of Yamba Formation consist of friable, pale-grey to pale-brown gypsiferous clay, grey pelletal clay, gypsum—quartz sand aggregates, and gypsum. Large recrystallised selenite crystals up to several centimetres long are commonly embedded in surface exposures of the friable gypsiferous clays. In places they form a gypcrete pavement. In the subsurface, the clays are less friable and are increasingly plastic in character.

At the margins of present-day playa lakes and salinas, the upper surface of the unit consists of a desiccated crust of fluffy gypsite, halite and gypsum—clay pellets. These desiccated lacustrine sediments merge laterally with pale-cream, pale-brown and white gypsite/quartz sand/soil admixtures of the adjacent lunettes. The lake floor sediment within modern playas consists of an upper layer of black sulphide-rich mud with an ephemeral salt crust. Mineral suites within the mud include sulphide and gypsum—clay laminites, dolomite, dolomitic clay, and dolomite-cemented sand (Bowler & Teller, 1986). The ephemeral salt crust consists mainly of gypsum and minor halite, but analyses of salt samples has also revealed the presence of bischofite, thenardite and mirabilite. The seasonal halite precipitates are not generally preserved, although minor local deposits occur in some salt lakes, such as those at Linga (Cane, 1962). The black sulphide-reducing muds are mostly underlain by thicker sequences (up to 2—4 m) of dark grey-blue, water-saturated clay with beds of crystalline gypsum mush, alternating with clay beds or thin gypsum—clay laminites. Locally, the sulphide-reducing muds directly overlie orange iron-stained sands (Loxton—Parilla Sands in some cases), whereas elsewhere they overlie older lacustrine clays (older Qly and Blanchetown Clay in places). At some sites, the saline lake deposits are associated with mounds and sheets of ferricrete,

dolomite and silcrete-cemented quartz sand (Figs 117, 145).

Each of the scattered occurrences of Yamba Formation is slightly different in character, and the sedimentology of fossil deposits has not been extensively studied. However, detailed descriptions of the Recent saline lacustrine sediments at Lake Tyrrell (Table 37; Teller & others, 1982; Bowler & Teller, 1986), provide analogues for some of the processes which are thought to have been responsible for the older deposits of the Yamba Formation.

Distribution and thickness. Modern and fossil saline lake deposits with associated gypsum and clay pellet deposits are entrenched within both the aeolian Mallee landscapes of the western Murray Basin and the western margins of the fluvial Riverine Plain (Fig. 143). In the north, extensive fossil evaporites are preserved on MANARA and IVANHOE. In the south, active salinas occur in the Buloke and Kerang regions (Fig. 143). Additional active salinas are also located in coastal areas, particularly adjacent to Lake Alexandrina. Saline lake deposits were probably more widespread in the past – as indicated by the extent of fossil lake systems with associated gypsum and clay pellet lunettes in both the Mallee region and at the western margins of the Riverine Plain (e.g. Hatfield Complex, Fig. 136). The composite lunettes of the Willandra, Darling River, and Darling Anabranch systems also have gypsum and clay pellet phases, indicating that the adjacent lakes have at times been saline. However, the lake sediments of these systems are only partly evaporitic in character, and on the enclosed 1:1 000 000 geological map they have mainly been included with undifferentiated lacustrine deposits (Ql).

The lake floor beds are rarely more than a few metres thick and do not generally exceed 10 m. The associated gypsiferous lunettes and other dune deposits are thicker, often up to 8 m, and locally exceed 20 m.

Outcrop and geomorphic expression. The unit is mainly associated with active and fossil groundwater discharge complexes and terminal lakes, where it forms aeolian-modified gypsite flats partly blanketed by younger aeolian dune deposits. Modern components of the unit are associated with ephemerally active playas and salinas, flooded by discharged groundwater and local run-off located within topographic lows. The playas in the aeolian terrains form irregularly shaped lake complexes entrenched approximately 1 to 1.5 m below, and within, older stranded lake floor sediments and adjacent aeolian dunefields (Fig. 144). The modern lakes are much smaller than the older stranded lake systems, reflecting a relative lowering of the groundwater table. They exhibit seasonally deposited halite crusts with rafted halite and halite polygons (Fig. 144). These areas are flanked by zones of efflorescence of gypsite and other salts. The shape of the active discharge lakes, and the configuration of remnant pedestals of former lake floors, partly reflect aeolian influence on erosion/preservation of lake shorelines by circulating lake waters. Fossil lake floors locally form extensive gypsite flats with local gypcrete terraces, but are partly blanketed by encroaching sand from adjacent dunefields. In places, they are overlain by deflated low hummocky dunes (nebkhas) of pale brown/grey/yellow gypsum-clay pellet material, derived from within the lake complex, and admixed with quartz sand. Deflated nested lunettes occur to the east and northeast of both fossil and active lake systems. Remnant traces of lunettes representing successive stranded shorelines are also evident within the gypsite flats and gypcrete terraces.

Internal geometry. Some clays are massive and unlaminated, whereas others are laminated. Internal sedimentary structures in some horizons have been destroyed by displacive gypsum, which forms pseudobedding. Near-horizontal laminae are evident in gypsum–clay couplets. Desiccation polygons that extend into the subsurface in the form of desiccation cracks occur within deflated lake margins and floors (Fig. 145). Depositional bedding in the associated lunettes has largely been destroyed by rootlets, postdepositional compaction and remobilisation of halite and gypsum.

Palaeontology. The shorelines of currently active lakes support algal mats which are seasonally desiccated. Following favourable rains and an influx of fresh run-off, shoals of brine shrimps appear. At certain times of the year some lake waters, and associated salt crusts, develop a distinctive pink hue. At the Linga salt lakes in Victoria, Cane (1962) related the pink colouration to the abundant presence of a microscopic halobiontic biflagellate phytozoan *Dunaliella salina* with a red carotene pigment. The potential for preservation of the above fauna is limited, however, and fossil remains have not been recorded in the Yamba Formation.

Age evidence. The saline lake sediments of the Yamba Formation are entrenched within, and therefore post-date lacustrine clays of the Blanchetown Clay. Palaeomagnetic analyses of core samples from Lake Tyrrell, undertaken by Bowler (1980) and An Zhi–sheng & others (1986) indicate that the evaporite sediments (Tyrrell beds) are all 'normally'

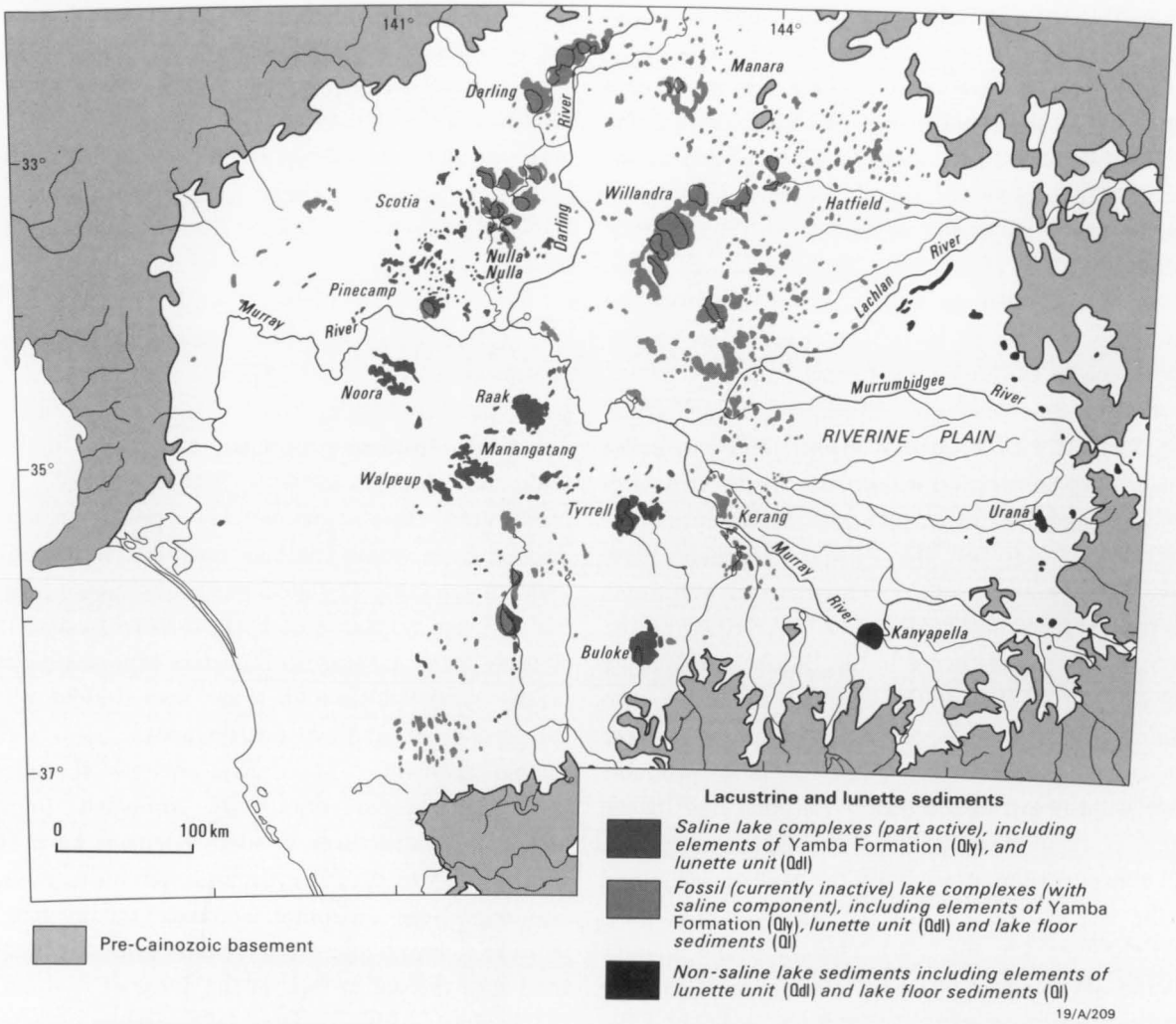


Fig. 143. Distribution of active and 'fossil' saline lake complexes (including Yamba Formation), and non-saline lacustrine deposits.

magnetised, indicating that sedimentation commenced above the level of the Bruhnes–Matuyama reversal. This provides a lower age limit of some 0.7 Ma. As discussed elsewhere, the onset of aridity in southeastern Australia is thought to have occurred in the period 0.4 to 0.7 Ma (An Zhi–sheng & others, 1986). Bowler & Teller (1986) reconstructed variations in the sedimentology and palaeohydrology of the Tyrrell beds over the past 36 000 yrs., based on events recorded in the uppermost 150 cm of sediment. A further 4.5 m of section is preserved beneath that examined. Based on average sedimentation rates, this possibly represents an additional 100 000 yrs. of record. However, given that sedimentation was not continuous, and that part of the sedimentary record has been deflated into the adjacent lunette, then the older components clearly extend well back into the Late Pleistocene. Gardner & others (1987) obtained thermoluminescence dates of Early Holocene (8500 $\pm$ 1800 yrs. B.P.) and Late Pleistocene (20 100 $\pm$ 3500 yrs. B.P.). At some localities, the formation underlies and/or is intercalated with aeolian sands of the Woorinen Formation with calcrete glaebules. Older components of the formation could therefore potentially be as old as 0.4 to 0.7 Ma. Much of the unit is currently being eroded

Fig. 144. (a),(b),(c) Located at Scotia Lakes groundwater-discharge complex (ANABRANCH) – (a) modern lake entrenched within stranded former lake-floor sediments consisting of gypsum, as shown in (b); (c) iron-cemented sand at groundwater-discharge site within lake floor; (d) rafted halite at Tooperoopna Lakes (ANABRANCH); (e) part of Raak Plains groundwater-discharge complex (MILDURA); (f) iron-cemented concretions, southwestern Lake Tyrrell (SWAN HILL); and (g) dessicated algal mat at eastern shore of Lake Tyrrell (SWAN HILL).

(a)

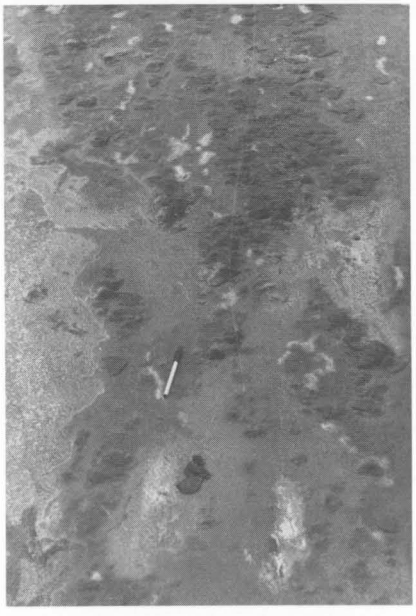
(b)

(c)

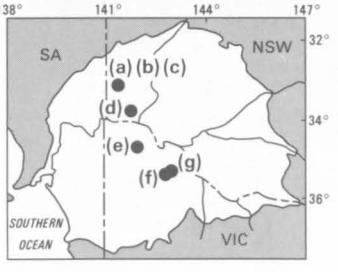
(d)

(e)

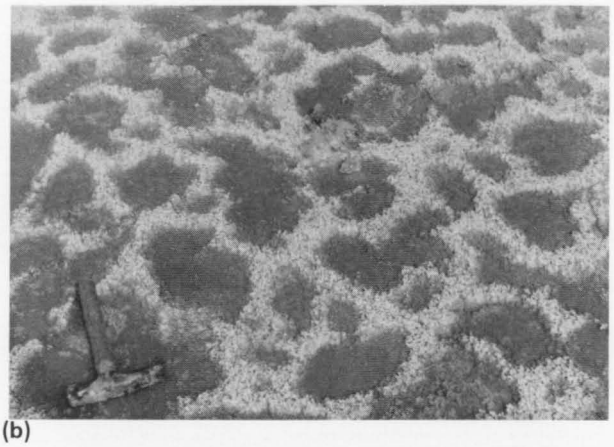
(f)



(g)



(a)



(b)

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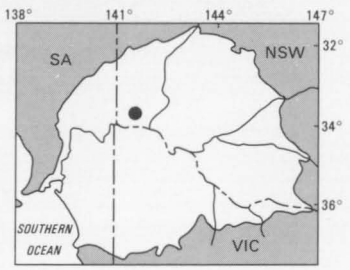


Fig. 145. Saline groundwater-discharge lake complex at Nulla Nulla Lakes (ANABRANCH), September, 1982, following prolonged period of drought – (a) dessicated crust at lake surface, consisting of 'fluffy' clay pellets, halite hoppers, gypsite and other salts; (b) dissolution of crust following rain, revealing presence of polygonal structures with bounding cracks infilled by halite, as shown on (c); (d) deflated lake floor showing extent of polygons and halite infilled cracks; (e) groundwater-discharge spring at southern end of Nulla Nulla Lakes (active despite drought); (f) stranded fossil groundwater discharge mound consisting of dolomitic and siliceous flagstones.

by deflation, but younger components continue to accumulate within the modern entrenched saline playas. Present occurrences occupy a much smaller area than older deposits, which can clearly be seen to underlie large areas of interdune sandplain within the Mallee dunefields of the western Murray Basin.

Characteristics. Older deposits are characteristically vegetated by salt-tolerant samphire, and are usually associated with deflated gypsum and clay pellet lunettes. On aerial photographs, the former groundwater discharge complexes can be identified by the complex interfingering patterns of deflated gypsum and clay pellet lunettes and remnant lake floor pedestals, as well as by an absence of the distinctive Mallee vegetation (Figs 144, 146). The modern salinas, which develop halite crusts during summer droughts, are characterised by high reflectivity on aerial photographs. In comparison with other lacustrine deposits, the active saline lake complexes are irregular in shape. During seasonal periods of desiccation, the modern lake sediments are coated by white powdery gypsite and other efflorescent salts.

Interpretation of environment of deposition. The evaporitic sediments of the Yamba Formation accumulated in inland sabkhas within the arid landscapes of the Murray Basin. Conditions favourable to deposition of the component sediment types can be related to past climatic variations and past fluctuations in lake water-level, as well as groundwater/lake-water interactions and consequent variations in salinity. In general, deposition of the saline components was predominantly associated with drying phases during transitional wet to arid periods, with inherited high groundwater tables (Bowler & Wasson, 1984). Galloway (1965) suggested the arid periods were coincident with periods of glacial maxima (Bowler, 1976b, 1978b; Sprigg, 1979, 1982), rather than with hot dry inter-glacial periods. Detrital clastic clay sediments are preserved in some lake systems. These were probably deposited in periods with wetter climatic conditions, and deeper lake waters with lower salinities, whereas evaporation, desiccation and deflation of lake floors was associated with dry windy climates and groundwater discharge into lake systems. The Murray Basin is a basin of internal groundwater drainage and most of the salt component of the Yamba Formation has been generated by evaporation at groundwater discharge sites, as well as by evaporation of surface run-off in terminal lakes. Rogers (1978) noted that some Upper Quaternary gypsum deposits on CHOWILLA and RENMARK may have been recycled from the underlying Blanchetown Clay.

The sedimentological response of individual saline lake systems to variations in climate and water budget also varies according to the position of the system in the basin. Many modern and fossil playa lake sediments, and their related aeolian sediments, are associated with groundwater discharge sites and salinas in low-lying areas of the basin. The location of many of these surface discharge complexes has been strongly influenced by the geometry and characteristics of the underlying aquifer systems. Some discharge complexes are located over zones where the underlying aquifer system has been truncated stratigraphically – e.g. where the Renmark Group aquifer system is laterally replaced by the Geera Clay of the Mid-Tertiary low permeability barrier (see Fig. 172). Elsewhere, the geometry of the underlying aquifer system has been influenced by the structural configuration of concealed basement features – e.g. the currently inactive Hatfield discharge complex (Fig. 136) is developed over a zone where the Renmark Group aquifer system thins dramatically, against the up-faulted eastern limb (Iona Ridge) of the concealed Ivanhoe Block at the northwestern margin of the Riverine Plain (Fig. 4). The extensive Raak Plains complex (Fig. 146) is located on the downthrown southeast side of the concealed northeast-trending Danyo Fault. Not all of the lakes are exclusively groundwater-dominated; several saline lake complexes form terminal lakes of surface drainage, with seasonal influx of freshwater and consequent differences in sedimentological response.

All of the lake complexes form small internal drainage basins and, after heavy rain, it is common for salt-encrusted surfaces of halite and gypsite to be entirely dissolved and recycled into the underlying sediments in the form of a dense brine. During the subsequent period of surface evaporation and desiccation, halite is progressively concentrated in the lowest parts of the lake complex, while salts carried into the shallow subsurface are concentrated within the underlying sediment to produce a gypsum mush. Periods of desiccation of the lake margins, and drying of the lake floors, in combination with the presence of halite in the capillary zone, result in the formation of puffy sand and silt-sized clay pellet aggregates (Fig. 145). Deflation of these lake floor sediments results in the transfer of the sand and silt-sized aggregates into adjacent lunettes, whereas fine-grained materials are progressively deposited over the adjacent aeolian landscape to the east. The

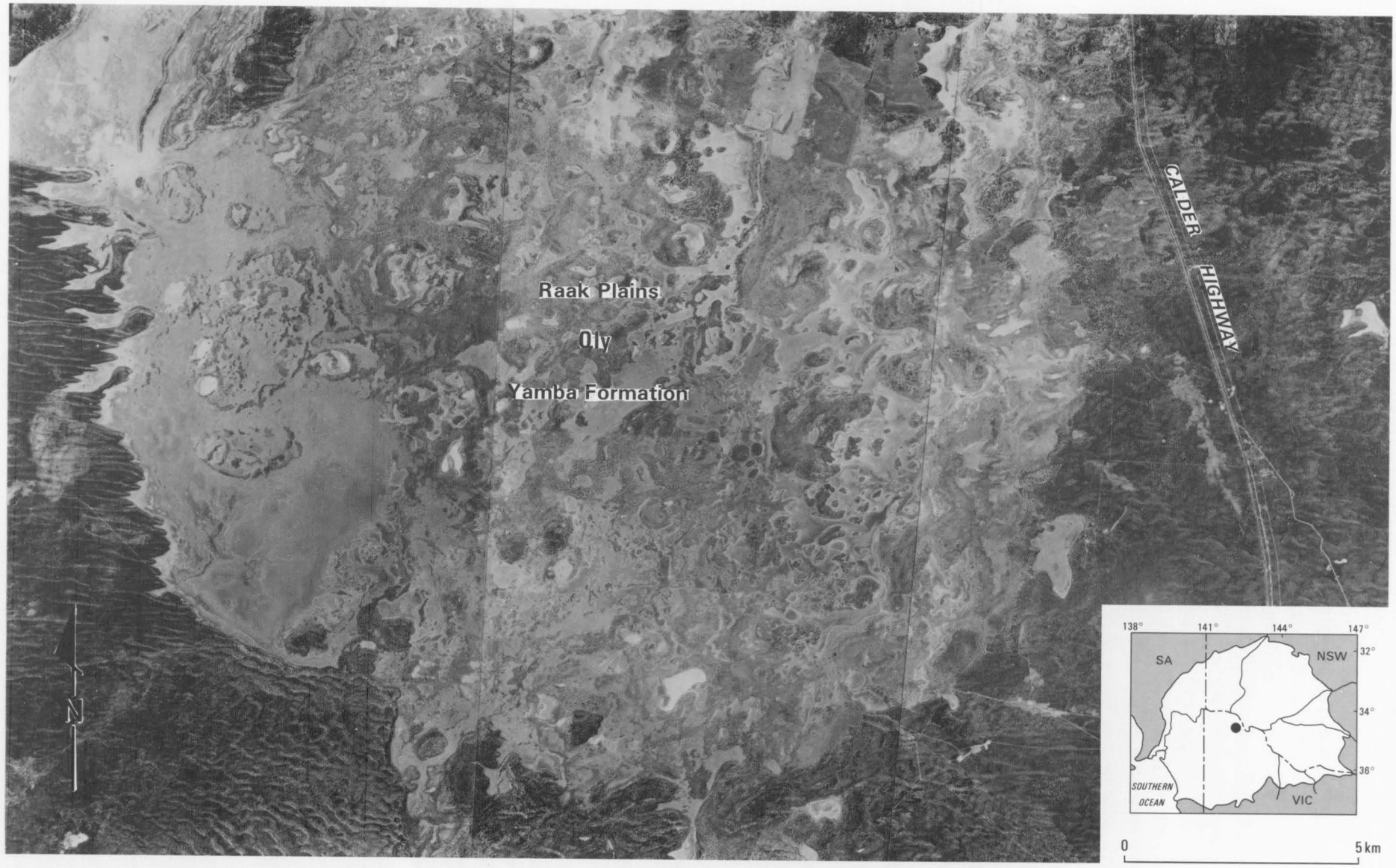


Fig. 146. Airphotomosaic of southern Raak Plains groundwater-discharge complex (eastern Mildura); photo from National Mapping RC9 Series, Mildura Run 6, Nos. 159, 163; photographed 20/10/1968.

high salt content of such downwind areas is indicated by the extensive areas vegetated by saltbush. Consequently, extensive aeolian gypsite deposits have accumulated to the east of saline lake basins. Part of the salts originate in the underlying aquifers, but in some terminal lakes part of the salt budget derives from the concentration of runoff by evaporation within a lake with no outlet.

Teller & others (1982) and Bowler (1983) have described the sedimentological processes which operate in Lake Tyrrell at the present day (Figs 147, 148; see 'Tyrrell beds' – Table 37), and Bowler & Teller (1986) reconstructed past water-level oscillations and related these to groundwater/surface-water interactions and sedimentary facies types. At various times over the past several thousand years, the water budget at Lake Tyrrell has been dominated by relatively fresh surface run-off, while at other times of progressively increasing aridity it has been dominated by underlying highly saline groundwater. A typical resulting sedimentological cycle (Bowler & Teller, 1986) commences with deposition of bioturbated randomly oriented clays in relatively low salinity, deep, lake waters. Precipitation of dolomitic carbonates in the muds begins after a decline in lake levels and a consequent increase in salinity (to 60–100 g/litre range). This is followed by sulphate saturation involving the primary precipitation of prismatic gypsum crystals (from brine at 120 g/litre) accompanied by seasonal deposition of gypsum–carbonate clay laminites, and laminated detrital clays. With increased evaporation, halite saturation occurs (salinity 359 g/litre) and groundwater discharge to the shallow lake sediments results in the precipitation of displacive discoidal gypsum in the subsurface. A further fall in the watertable is accompanied by seasonal development of a desiccated zone of fluffy pelletal clay aggregates, and deflation of the lake floor. If water levels fall below the capillary zone, the top of the cycle is marked by a layer of pedogenic weathering and remnant vegetation. Within the preserved succession at Lake Tyrrell, Bowler & Teller (1986) identified several such hydrologic cycles, reflecting past subtle climatic changes.

At Lake Tyrrell, ironstones (i.e. iron-cemented sands; Fig. 144) occur where groundwater discharge springs traverse the southwestern lake margins (Teller & others, 1982; Macumber, 1983; Bowler & Teller, 1986). Regional groundwaters are acidic (pH values of 4.5 or less; Macumber, 1983) and contain dissolved iron. The iron is precipitated in the neutral zone at the interface between the acidic groundwaters and alkaline lake deposits. A similar origin has been postulated for relict ferricrete deposits at Raak Plains (Fig. 117; Macumber, 1983), and at several other modern and ancient groundwater discharge complexes (e.g. Scotia Lakes on ANABRANCH). By contrast, groundwaters at the Nulla Nulla lake complex are less acidic and have deposited carbonate (dolomite-cemented sands) in the spring zones.

The sedimentological conditions at Lake Tyrrell are not entirely typical of other lake systems in the Murray Basin, each of which is in some way unique. For example, many of the other saline lake deposits of the western Murray Basin do not have sediment or water input from ephemeral streams and rivers, and consequently display only the more arid-phase lithology types. In contrast to present-day Lake Tyrrell, the fossil discharge complex at Hatfield (Fig. 136) is characterised by deflated, vegetated lacustrine systems, because the underlying groundwater table is currently below the capillary zone.

Stratigraphic nomenclature. The formation was named by Firman (1966c, 1973) after the Yamba Railway Siding on the Murray Bridge to Renmark line.

Type section. Firman (1973) nominated a number of bore sections in the Noora–Yamba area in RENMARK as being representative of the unit. Descriptions of the sections are documented in Johns (1952a) and localities are shown on the RENMARK geological map (Firman, 1972).

Stratigraphic relationships. Firman (1973) excluded the saline crusts of currently active ephemeral lakes from his definition of the Yamba Formation. Throughout much of the basin, however, these saline crusts are intimately associated with the older lacustrine and lunette sediments, and in this Bulletin have therefore been included in the Yamba Formation, along with all other Quaternary saline lake deposits. The formation overlies and, in many places, is disconformably entrenched within the Blanchetown Clay. Locally, the unit is possibly transitional with saline facies sediments of the upper Blanchetown Clay. At some sites, the unit is entrenched below the level of the Blanchetown Clay, and rests directly on Loxton–Parilla Sands. Older deposits of the unit are disconformably overlain by, and are locally intercalated with, aeolian sands of the Woorinen Formation. In South Australia, Firman (1973) included gypsiferous lunettes and longitudinal dunes in the Yamba Formation – some of these are included in 'Qdl' in this Bulletin.

Aquifer characteristics. The saline lacustrine sediments of the Yamba Formation do not themselves

Fig. 147. Airphotomosaic of Lake Tyrrell, western SWAN HILL; photos from National Mapping RC9 Series, Swan Hill Run 3, No. 92, photographed 28/11/1964, and Run 4, No. 210, photographed 14/11/1964.

TABLE 37. UPPER PLEISTOCENE – HOLOCENE TYRRELL BEDS (included in Qly)

Unit: Tyrrell beds

Age: Quaternary, Late Pleistocene to Holocene

Map symbol: included in Qly

Remarks. Each saline lake deposit in Murray Basin displays unique combination of sedimentological characteristics. Processes which operate at Lake Tyrrell, however, provide modern analogues for formation of other saline lake deposits. Descriptions based largely on Teller & others (1982), Bowler & Teller (1986), who referred to modern lacustrine sediments at Lake Tyrrell (Fig. 147) as 'Tyrrell Beds'.

Lithology. Blue-grey, green-grey, and grey silty clay, dolomitic calcareous clay, gypsum-clay laminites, prismatic gypsum laminae and thin beds, displacive discoidal gypsum beds, minor palaeosols, black sulphide-rich bacterial mud, and minor laminae of aeolian-derived coarse-grained silt and sand.

Several cyclical sediment associations have been identified down-sequence:

(a) During summer months, lake floor partly covered by ephemeral crust of up to 10 cm of halite, intercalated with quartz silt and sand laminae. Minor laminae of euhedral gypsum in form of gypsum-halite couplets also occur within salt crust; small amounts of bischofite, thenardite and mirabilite present – these components re-dissolve after winter rains and halite diffused into brine in underlying Loxton – Parilla Sands. Minor laminae with red-stained quartz (aeolian dust) also present. Gypsum mainly clear equant to prismatic crystals, elongated parallel to c-axis. At west margins of lake floor, reddish-brown ferric iron deposits precipitated from groundwater at interface of permanent springs with lake waters, form distinctive iron-cemented mounds and polygonal concretions (Fig. 144) – associated with high radioactivity (Macumber, 1983).

(b) Salt crust underlain by 6 – 10 cm of black, sulphide-rich mud, with sulphate-reducing bacteria, and up to 2% of total organic carbon; black due to 5% of iron sulphide – sulphate largely absent (table 5 of Teller & others, 1982).

(c) Layer of black mud (above) underlain by grey, greenish-grey, and blue-grey mud – sulphide reverted to sulphate (15 – 19% crystalline gypsum) – unlike gypsum of surface brines, subsurface crystals in modern muds beneath basin margins discoidal in shape, and displacive within mud (range in length from few mm to several cm – up to 20 cm), hexagonal in plan, contain clay inclusions, and locally form sheet-like beds up to 20 cm thick. Concentrations associated with groundwater springs at west margins of lake. Similar layers of pure prismatic sedentary gypsum occur in older sediments, where form interlocking crystalline gypsum mush – these, however, occur in clay-free laminae, form thin 'sugary' beds within clay, and were precipitated directly from lake brine.

(d) Older, more deeply buried parts of profile have non-laminated clays, laminae of micritic dolomite, high magnesium calcite clays alternating with laminated clays, and gypsum-carbonate clay laminites.

(e) Non-laminated clay beds bioturbated, up to 40 cm thick, display random clay orientations, locally with muscovite reworked from underlying Blanchetown Clay and other detritals introduced by ancestral Tyrrell Creek; some horizons of sand-size pelletal clay of aeolian origin.

(f) Several pedogenically altered horizons also identified within sequence (Bowler & Teller, 1986); palaeosols associated with prismatic jointing and root tubules.

Distribution and thickness. Occur beneath and around margins of present-day Lake Tyrrell (60 km west of Swan Hill, SWAN HILL). Lake and associated islands extend over 185 km^2, and 20 km N–south (Fig. 147). Interpreted sections across Lake Tyrrell indicate up to 10 m of evaporitic lacustrine sediments preserved.

Outcrop and geomorphic expression. Tyrrell Creek floods lake during winter months. During summer months, lake floor desiccated to form salt flats. Lake floor (42 – 44 m.a.s.l.) entrenched 15 – 30 m below Mallee dunefields. Irregularly shaped vegetated small islands of stranded lacustrine and aeolian deposits up to 10 m above lake floor. Narrow sandy beach and irregular wave-cut embankment flank west shoreline. East margins of lake shelve up to stranded beaches and topographically prominent nested clay pellet lunettes.

Palaeontology. Leathery blistered algal mat overlies groundwater saturated lake shores of sandy clay with gypsum. Fossil Coxiella sp. (brackish water mollusc) in stranded beach deposits.

Age evidence. Palaeomagnetic data from underlying Blanchetown Clay indicate deposition of Tyrrell beds commenced after Bruhnes – Matuyama magnetic reversal (An Zhi – Sheng & others, 1986), and older components could be as old as 0.4 Ma. Radiocarbon dates from stranded beaches Macumber (1983) suggest Lake Tyrrell last filled with deep water some 32 000 yrs. BP. Luly & others (1986) found uppermost metre to be entirely Holocene. Bowler & Teller (1986) identified at least 3 cycles of alternation from lake-full to lake-dry conditions, and reconstructed history of lake over past 36 000 yrs. (top 150 cm of section).

Environment of deposition. Present-day Tyrrell beds deposited within large ephemeral lake. Past variations in sedimentological processes thought to reflect complex interplay between climatic and groundwater conditions (Fig. 148) – response of lake to climatic change rapid, but considerable lag in response of groundwater table. At present, saline groundwater enters lake via small springs and seepages; summer evaporation leads to saturated brine and eventually halite crusts (up to 10 cm thick). Development of gypsum-halite couplets attributed to partial solution of salt crust during summer rains. Most rain falls in winter, when lake filled with up to 1 m of water, and saline brines recycled into underlying regional Pliocene Sands aquifer system.

Black colour of anoxic muds, beneath halite crust and brine, due to sulphate-reducing bacteria Desulfovibrio. Below upper 5 – 10 cm bacteria destroyed by burial or oxygenated groundwater – resulting in precipitation of discoidal gypsum, crystallised within mud matrix, from saturated groundwater brine (prismatic forms initially precipitated from surface brines largely destroyed within layer of sulphate-reducing bacterial mud). Minor fine-grained clastic components derived from aeolian source, erosion of lake margins, and from Tyrrell Creek in south.

Stranded beaches deposited when water levels considerably higher than present. Lunettes to east accumulated largely during periods when groundwater levels slightly lower than present, when deflationary erosion removed 4 – 5 m of sediment from lake floor (Bowler & Teller, 1986) – mode of formation (Bowler, 1983) involved desiccation of clay of lake floor during hot dry windy conditions. Salt crystallization and development of sand and silt-sized clay pellets, followed by deflation and deposition over adjacent lunette.

Stratigraphic nomenclature and type section. Named after Lake Tyrrell by Teller & others (1982), who documented representative suite of cores.

Stratigraphic relationships. Tyrrell beds unconformably entrenched within Pleistocene Blanchetown Clay and adjacent dunefields of Woorinen Formation (Macumber, 1983; Bowler & Teller, 1986).

Economic geology. Halite harvested and bagged in small salt works at SW of lake.

Data sources. Teller & others (1982), Macumber (1983, in press), and Bowler & Teller (1986).

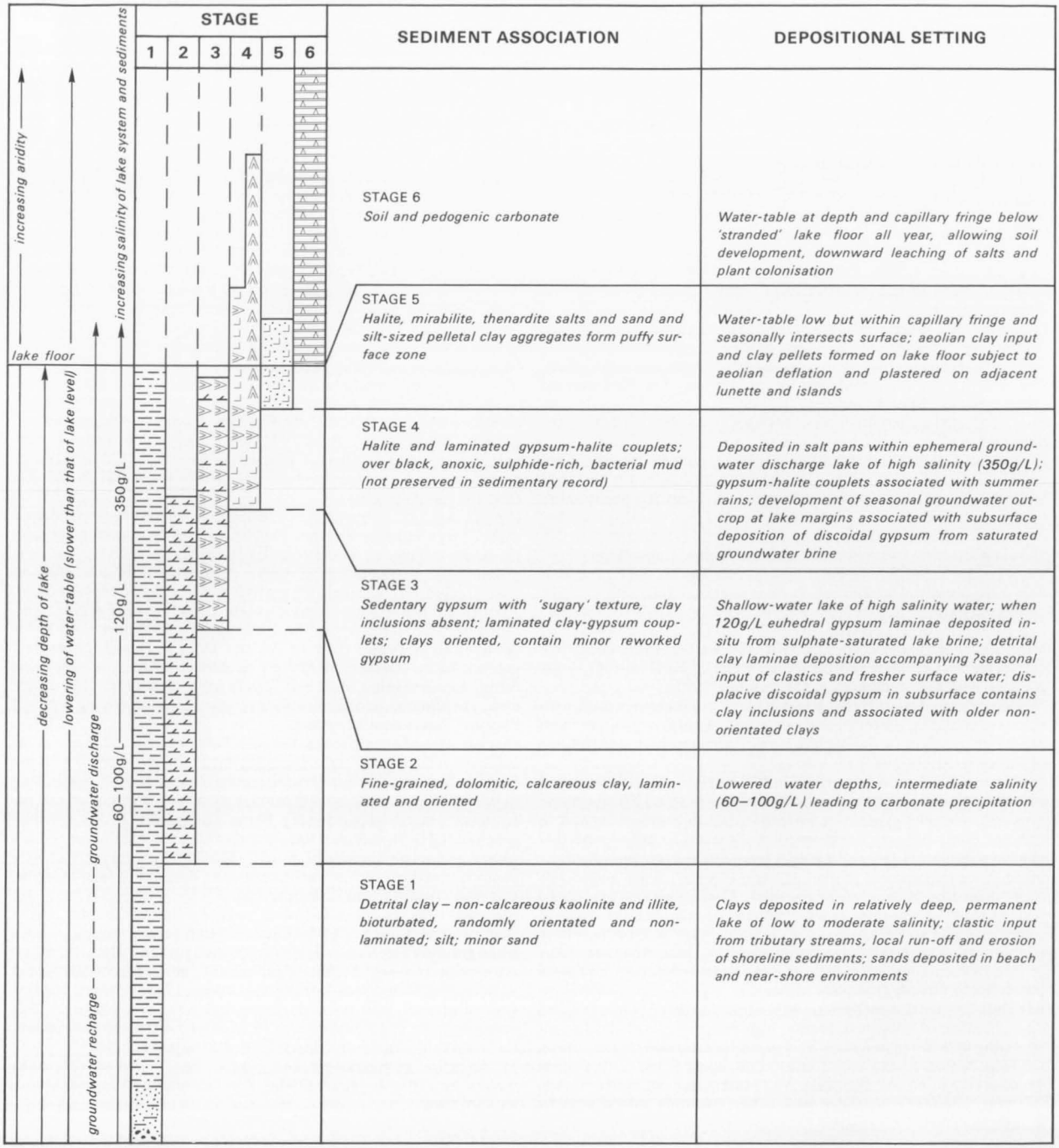


Fig. 148. Conceptual representation of stages of evolution of lacustrine sediment associations at Lake Tyrrell (SWAN HILL), accompanying progressive drying of lake system and lowering of groundwater table. Based on reconstructions of Bowler & Teller (1986); an overlap of sediment associations occurs because of climatic oscillations, seasonal variations, and variations of conditions within different parts of the lake system. The surface waters of the lake respond rapidly to climatic change, whereas the response of the groundwater table shows a lag.

form aquifers, but as noted above the location of many of these deposits reflects the configuration of underlying aquifer systems. The saline lake complexes are major sites of evaporation, and are often underlain by brine pools within the Pliocene Sands aquifer system.

Economic geology. Extensive, locally worked, gypsum deposits, as well as minor halite occur within the Yamba Formation. Some of the former lake systems have now been artificially developed as evaporation basins for the disposal of saline irrigation water, and intercepted saline groundwater.

Data sources. South Australian occurrences of the unit are described in Johns (1952a,b, 1953, 1954) and Firman (1966c, 1972, 1973). Aspects of saline lake genesis are discussed in Cane (1962), Bowler (1970a, 1971, 1973, 1976a,b, 1978b, 1981, 1983), Macumber (1983), and Magee (1986). The sedimentology of the Quaternary evaporites at Lake Tyrrell and their relationship to hydrological changes have been documented by Teller & others (1982) and Bowler & Teller (1986). Johnston & Kamprad (1988, 1989) reported on the use of image processing of Landsat data to identify salinised areas.

Unit: Undifferentiated Quaternary lacustrine deposits
Age: Late Pleistocene to Holocene
Map symbol: Ql
Component unit: Cohuna Silt
Associated units: Equivalent to the Yamba Formation, Tyrrell beds and other saline lake deposits (Qly); Unnamed Quaternary lacustrine-derived aeolian lunette deposits (Qdl); Coonambidgal Formation and other undivided alluvial deposits (Qa)

Remarks. The lacustrine sediments that are preserved in the present landsurface of the Murray Basin form a composite unnamed morphostratigraphic unit, which in detail consists of a number of lithologies deposited in a variety of physiographic settings.

Lithology. Most lake floors of the Murray Basin are underlain by unconsolidated, 'plastic' to 'sticky', finely laminated to obscurely bedded, massive grey clay, silty clay, silt, humic clay and grey palaeosols. Many lake deposits are also associated with medium to fine-grained quartz sand preserved as beach deposits at former strandlines. In some lakes, minor sand and granular conglomerate deposits are preserved in lacustrine deltas where stream channels enter, or formerly have entered, the lakes (Fig. 149). Some lacustrine sediments within the floodplain of the Murray River are the deposits of ox-bow lakes ('billabongs') cut off from major fluvial channels, and are characterised by high biologic production resulting in layers of carbonaceous peaty sediments. During dry periods, some seasonally flooded lake floors consist of grey, desiccated and cracked, friable, silty clays. These are often vegetated by grasses and are consequently humic with abundant fine rootlet material. Dark brown peats and black humified soils occur within many swamp deposits (Stephens, 1943; Miles, 1956). Lacustrine carbonates form a prominent component within some coastal lake sequences.

At the eroded western margin of Lake Mungo, Bowler (in Magee & Beaton, 1985) noted the presence of 2 m of grey gypseous clays with broken lacustrine dolomite plates, consisting of microcrystalline and sparry dolomite-cemented fine quartz sands with heavy minerals. Grey silcrete ridges with a subdued topography extend from the stranded western shorelines of Lake Mungo and the Chibnalwood lakes. At Kow Swamp, the lake floor sediments (Cohuna Silt) form a silty clay plain, flanked by a narrow belt of near-shore lacustrine silt with varve-like laminae of very fine sand (Thorne & Macumber, 1972; Macumber, 1977). These are up to 1.5 m thick, and are overlain by a thin bed of clean fine-grained sand, further overlain by a band of unionid shell debris and more silt. The silt component contains well-sorted quartz silt grains cemented by authigenic carbonate, and is overlain by a thin red-brown soil profile.

Distribution and thickness. The deposits of both active and recent lakes have been included in the Ql unit. They are widely distributed throughout the fluvial and aeolian landscapes of the Murray Basin in a variety of physiographic settings (Fig. 143). These comprise flood-plain lakes and swamps, terminal lakes, former groundwater discharge lakes, interdune deflation hollows and coastal lake complexes. They are associated particularly with the Riverine Plain (Figs 136, 150), where numerous swamps and lakes occur on the extensive floodplains of the major rivers, including the Murray, Murrumbidgee and Lachlan. Large lakes, and inter-connected lake and fluvial channel complexes are associated with the Darling River near Menindee, and with the Darling Anabranch (Figs 140, 142, 156). Large lake systems also occur along some of the rivers which terminate in the Mallee dunefields (e.g. Lake Hindmarsh and Lake Albacutya on the Wimmera River, and Lake Buloke on the Avon River).

Fig. 149. Airphoto of Lake Mulurulu on Willandra Creek, northern POONCARIE; photo from National Mapping RC9 Series, Booligal Run 1, No. 53; photographed 13/10/1968.

Deposits of lacustrine sediments are found also in chains of numerous small lakes and swamps located in the swales between the Pliocene Loxton–Parilla sand ridges, particularly in the southwestern Wimmera landscape in HORSHAM (see Figs 91, 92 and enclosed 1:1 000 000 geological map), and between the stranded beach-ridge complexes of the Pleistocene Bridgewater Formation (see 'Padthaway Formation').

In many areas of the aeolian Mallee landscape in western N.S.W. and northwestern Victoria, runoff is almost entirely restricted to small basins of internal drainage. Some small lakes are entrenched within older lake deposits adjacent to nested deflated lunettes. These small areas are commonly underlain by saline clays and soils, due to former groundwater discharge and internal evaporation of runoff, as well as wind-blown salts derived from the larger lake complexes (e.g. small lakes to the east of Lake Victoria on ANABRANCH). Some of these are shown as undifferentiated 'Ql' deposits on the accompanying geological map, but where they are sufficiently large and have a significant proportion of gypsum they are differentiated as the 'Yamba Formation'.

The thickness of these lacustrine deposits is highly variable, but is generally only a few metres and is unlikely to exceed 10–20 m. The thickest-known section is in equivalent sediments of the Tyrrell beds, where up to 10 m of evaporitic sediments have been encountered. At Kow Swamp, the unit (Cohuna Silt) is up to 1.5 m thick and extends over 25 km^2. In an ox-bow lake at Moorna East, on the Murray River floodplain near the tri-state border, Gill (1973a) found only 20 cm of clay over a mottled palaeosol.

Outcrop and geomorphic expression. The lake and former lake deposits of the basin form flat-lying areas, which can extend over a few to several hundred square kilometres. Some of the lakes are

kidney-shaped (Figs 140, 142), though others are elongate and follow old fluvial channels, and others are irregular in outline. Some hold permanent standing water, but many are ephemeral and subject to seasonal flooding (e.g. Darling Anabranch Lakes), and others are entirely dry fossil features (e.g. Willandra Lakes). Adjacent to the floodplains of the larger modern rivers, they are usually vegetated by cane grass and bordered by woodland or swamp. The Willandra Lakes system has been dry for at least 14 000 yrs. (Bowler, 1971) and is vegetated by low scrub. During much of the year, the ephemeral lakes, such as the Darling Anabranch lakes, are dry, and large cracks appear in the grass-covered lake floors. Other abandoned lake floors are entirely vegetated by either grassland, low to tall shrubs or woodland – depending on the relative level and salinity of the underlying water-table, as well as the salinity of the soil. Some of the more saline depressions and swampy areas within the dunefields are transitional with those of the Yamba Formation and are vegetated by various forms of saltbush.

The modern northerly flowing rivers and streams which drain the northwestern flanks of the Victorian highlands have insufficient water to reach the Murray River. Consequently, many of these terminate within intermittent to ephemeral lakes and swampy flats. Similarly, at the western margin of the basin many creeks draining the South Flinders Ranges terminate within the aeolian landscape, although the former courses of some of these drainage lines are readily identifiable, beneath a thin blanket of aeolian deposits, on both topographic maps and aerial photographs. This is particularly true around the northern fringes of the basin where a former fluvio-lacustrine plain is readily identifiable beneath a veneer of sand, sandy loess, and parna ('Qdp'). Some small lakes that formed along these former drainage lines have been preserved within the present landscape as basins of internal drainage. They are generally entrenched a few metres beneath the general landscape surface.

Palaeontology and age evidence. Coquinoid banks of small *Corbicula* shells occur within the lake floor sediments of Lake Menindee. Some lake sediments, particularly the beach deposits, contain brackish to saline-water *Coxiella* shell fragments, whereas others, such as the marginal-lacustrine sediments at Kow Swamp (Macumber, 1977), preserve freshwater *Unionid* remains. Past variations in climate have resulted in periods when the lakes have dried-up and the lake-floors supported savannah grasslands or forest vegetation. At Kow Swamp, for example, pollen samples (Wright, 1975) suggest that the modern tree cover became established between 7500 and 8000 yrs. B.P. Human burial sites are found mainly in the adjacent lunette deposits, but at Kow Swamp skeletons were found in the nearshore lacustrine silts (Thorne & Macumber, 1972; Macumber & Thorne, 1975; Macumber, 1974, 1977, 1983). Radiocarbon dates from these human burial sites indicate that deposition of the Cohuna Silt pre-dates 13 000 to 9000 yrs. B.P. Radiocarbon dates from intercalated *Unionid* shells gave an age of 10 879 $\pm$ 100 yrs. B.P. The detailed age of most lake sediments is unknown, but probably ranges through the interval from Late Pleistocene to Recent. Many lake sediments that are associated with the modern floodplains are clearly of Holocene age, whereas others are associated with lunettes which are older than the limits of the radiocarbon method and could be as old as 0.4 to 0.7 Ma (see description of 'Qdl'). Stranded lake sediments at the western margin of Lake Mungo, for example, underlie a layer of soil and are older than the limits of the radiocarbon method (Bowler, *in* Magee & Beaton, 1985).

Characteristics. The lake deposits of the Murray Basin form a morphostratigraphic unit (Ql), identified mainly on the basis of geomorphic expression. The detailed lithology can vary from one lake to another reflecting variations in local palaeohydrologic controls.

Interpretation of environment of deposition. The sediments of the unit were clearly deposited in a range of lacustrine environments. These were sensitive to a number of controls, such as palaeoclimate, Quaternary sea-level changes, and related fluctuations in groundwater levels and chemistry. Some lake sediments, such as those at Lake Tyrrell, have a long history of fresh surface water domination alternating with periods of saline groundwater domination (see 'Qly' and 'Tyrrell beds'). A similar alternation of saline and freshwater dominated phases is recorded in the stratigraphy of lunette sediments adjacent to many other lake systems (see 'Qdl'; e.g. Willandra Lakes), whereas some are entirely freshwater dominated (e.g. Lake Kanyapella), and others are dominated by the discharge of saline groundwaters (included in the Yamba Formation).

Stratigraphic nomenclature. The unit is unnamed apart from localities where the lake sediments have been described in detail. At Kow Swamp in south-western DENILIQUIN, for example, the lacustrine sediments were named the Cohuna Silt by Thorne & Macumber (1972).

Stratigraphic relationships. The unit is a surface mor-

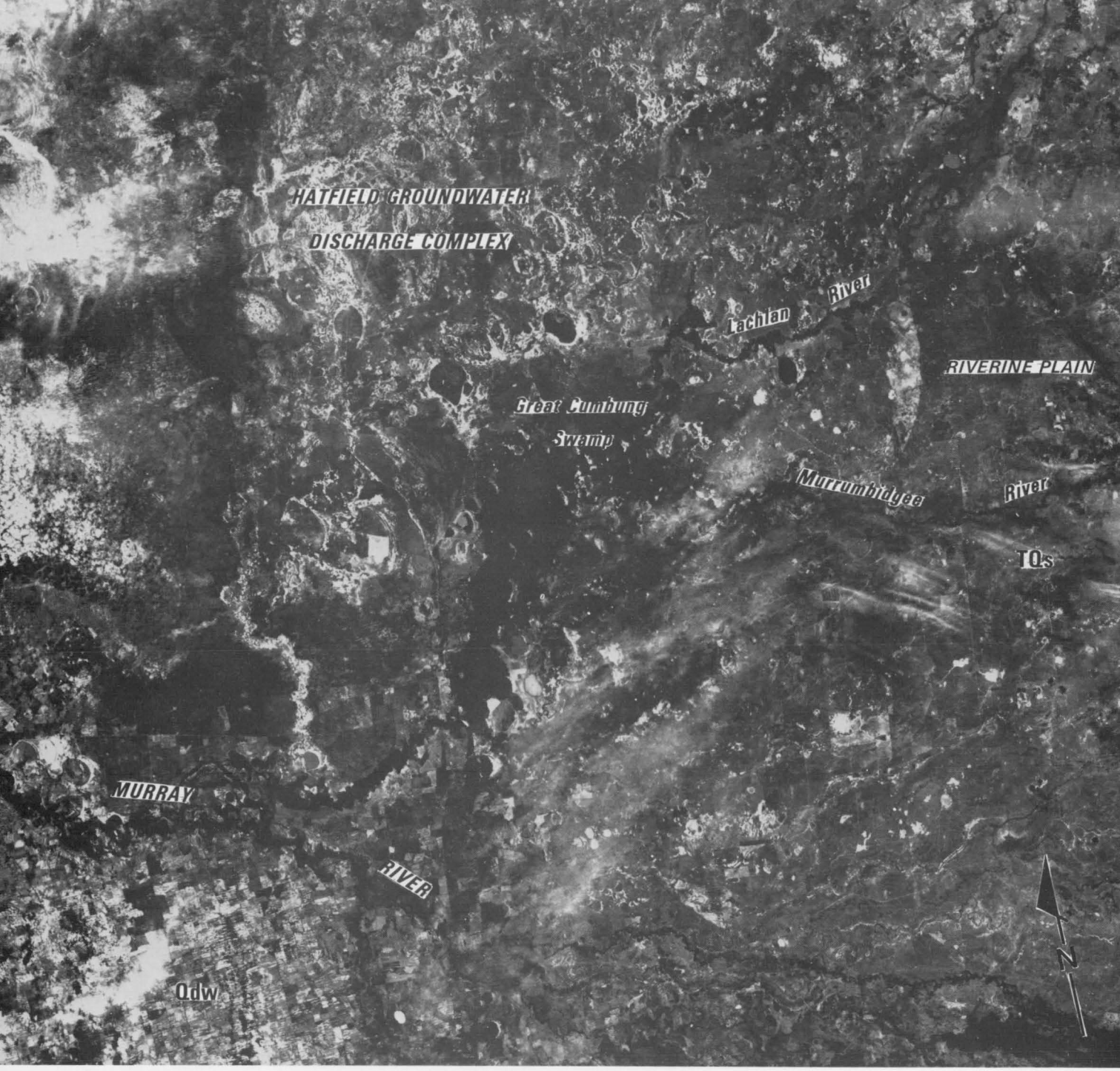


Fig. 150. LANDSAT scene of fossil (currently inactive) Hatfield groundwater-discharge complex, western Riverine Plain, N.S.W.

phostratigraphic one, and includes the sediments of active lake complexes and the surface deposits of Upper Pleistocene – Holocene ancestral lakes. Older subsurface equivalents with no surface expression are included in the fluvio-lacustrine Shepparton Formation or Blanchetown Clay. In the Late Pleistocene, many surface lakes were of much greater extent than they are at present, and consequently stranded sediments of former lakes are locally disconformably overlain by the Woorinen Formation, Qdu, Molineaux Formation/Lowan Sand, and Yamba Formation. The saline lacustrine sediments of the

Yamba Formation and other saline lake deposits are essentially a variant of the Ql unit, and many salt lake complexes have undergone freshwater phases. Similarly, many of the Ql deposits are associated with gypsum and clay pellet lunettes.

Economic geology. Some lakes (such as Lake Menindee and Lake Victoria) are used as water storage basins, using water captured during periods of flood. This water is then released to maintain river levels, particularly during periods of drought. Other lake floors are irrigated and cropped (e.g. Lake Tandou on MENINDEE).

Data sources. Geomorphic and geological descriptions of lake systems of the Murray Basin are given in Bowler (1970a, 1971), Gill, 1973a, Bowler & Magee (1978), Thorne & Macumber (1972), Macumber (1974, 1977, 1980, 1983), Macumber & Thorne (1975), and Ross (1981). Younger deposits of the lower Murray swamplands have been described by Taylor & Poole (1931). Interdune coastal lakes in the Kingston Southeast (NARACOORTE) and Beachport (PENOLA) areas were described by Mawson (1929) – see also 'Qhl' and 'St. Kilda Formation'.

Unit: Unnamed Quaternary aeolian dune deposits
Age: Quaternary, mainly Late Pleistocene to Holocene
Map symbol: Qdu
Associated unit: Equivalent to Molineaux–Lowan Sands (Qdm)

Lithology. The unit consists primarily of unconsolidated red-brown to pale-orange siliceous sand. The sand is mainly medium to fine-grained quartz, with residual red sesquioxide stains from clay cutans. The sand grains are admixed with humic debris consisting of twigs, leaf litter, and rootlets. Minor sand-size grains of reworked calcrete, as well as soft fragmented calcareous and gypseous filamental rhizoliths after rootlet material, are also preserved within the sand. The clay content is low in comparison with the Woorinen Formation. The unit has been only weakly modified by pedogenesis, and a catenary profile is generally absent. Minor rhizolithic concretions are present, but the calcretes which characterise the older aeolian deposits of the Woorinen Formation are largely absent.

Distribution and thickness. The unit forms several elongate, easterly or northeasterly trending aeolian dunefields in western N.S.W. (Fig. 130), but is confined in distribution to areas to the west and east of the Darling River and the Darling Anabranch, north of the Murray River. Equivalent dune sands, south of the Murray River, are included in the Molineaux–Lowan Sands. Extensive dunefields of Qdu are particularly well-developed in the region east of the Darling River and northwest of the Riverine Plain. The largest complex, transected by the Willandra Lakes system, extends north–south for 40 km and west–east for 130 km from the Darling River near Pooncarie (eastern ANABRANCH) across POONCARIE to the western margin of BOOLIGAL (Fig. 142).

Outcrop and geomorphic expression. The unit occurs at the surface of the basin, where it is well exposed. Many of the dunefields have the configuration of mega-blowout features, and are elongated in an east-northeasterly direction. To the east, they form increasingly narrow tongues of sediment, and are broadest at their western margins where they merge with the underlying landforms, from which they are partly derived.

Individual dunes are characterised by sharp crests, which are locally linear, but generally appear to be irregular to sub-parabolic in plan. Some dunes are separated by narrow interdune depressions and corridors, but swales are poorly preserved, narrow, irregular in shape, and have largely been buried beneath superimposed duneforms. The dunefields consist of composite interference patterns of closely spaced and superimposed parabolic and linear dunes, creating the impression of irregular and 'jumbled' dune forms. The trailing limbs of the parabolic dunes diverge up-wind and are a few hundred metres to several kilometres in length. They converge down-wind to form sharp-angled apices pointing in an easterly or east-northeasterly direction (Fig. 151). The convergent apex of each major dune forms the highest point and is elevated up to 10 m above the adjacent flanks and fore-dune areas. High-angle bedding laminae are preserved beneath steeply inclined avalanche slip faces. The trailing limbs of the parabolic dunes decrease in elevation to the west, where they are mainly buried beneath the frontal avalanche faces of succeeding dunes.

At present, the dunes are largely stabilised in fixed positions by thin Mallee scrub. The soil cover is not well-developed, however, and the dunes are readily remobilised and susceptible to erosion. Some dunes are currently mobile, and are characterised by deflation hollows lacking vegetation and covered by wind-rippled sand. These deflation hollows are developed both along axial ridge crests and within inter-ridge depressions. The recently eroded sands have mainly been heaped into small local hummocky, but steep-sided, blowout dunes of free-flowing sand

lacking vegetation and advancing over adjacent scrub. In lower-lying areas, the sands have been heaped into elongate hummocky dunes vegetated by grasses. This local mobilisation of dunes occurs where the vegetation cover has been thinned by drought, fire or overgrazing. The presence of sharp dune crests and steep slip faces on many vegetated and apparently stabilised dunes suggests that some of these may have been locally mobile in the recent past.

Internal drainage patterns are almost entirely absent within the highly porous Qdu dunefields, and in some areas where the unit has advanced over older or adjacent units many former drainage channels have been partly buried by advancing dunes. In contrast, some of the larger lakes and fluvial channels, such as the Willandra Creek system, have largely maintained their shape and course through the dunefields.

Palaeontology and age evidence. Deflation hollows within the dunefields reveal the accumulated remains of marsupial bones and Aboriginal artifacts, such as former fireplaces and stone implements. Many of these artifacts consist of ferricrete or silcrete materials.

The unit forms dunefields which are mainly stable and inactive today, despite the presence of locally mobile components in some areas. The apparent superimposition of the Qdu dunefields, over many of the older Pleistocene morphostratigraphic units of the basin, suggests a relatively recent age of activation. This is supported by the preservation of high-angle slip faces, sharp dune crests, and general lack of pedogenesis. However, the dunefields east of the Darling River are transected by the Willandra Lakes system, indicating that the last major period of sand mobilisation largely predates, or was coeval with, the last lacustral phase in the now dry lake system, and therefore probably predated 14 000 yrs. B.P. Bowler & Magee (1978) suggested that mobilisation was synchronous with the last major active phase of lunette formation at about 18 000 to 16 000 yrs. B.P., and that the active dunefields were trimmed by wave erosion at the lake edges. Final drying of the lakes must have largely post-dated stabilisation of the dunefields, although a number of large lobes of dune sand have advanced short distances across the western floors of Lake Garnpung and Lake Arumpo, indicating some local degree of post-lacustral dune migration.

Characteristics. The unit is characterised by its distinctive geomorphic expression in combination with its high quartz sand content, poorly developed soil profiles, absence of sheet calcrete, and lack of pedogenic calcareous glaebules (apart from minor soft gypseous and calcareous rhizoliths). The unit is similar in morphology to the Molineaux–Lowan Sands, but the quartz sand is rubified, and was possibly derived from re-mobilised and sifted Woorinen Formation, whereas parts of the relatively clean, yellow Molineaux–Lowan Sands in the southern Murray Basin may have been derived directly from the underlying Loxton–Parilla Sands. Sands of Qdu have been recognised only north of the Murray River, whereas those of the Molineaux–Lowan Sands are recognised only to the south. There is, however, a transition between the two end–member types, and some dunefields in central-western areas of the basin could be placed in either unit.

Interpretation of environment of deposition. The geomorphic expression of the 'Qdu' sand indicates that the unit was deposited by aeolian processes, which resulted in the creation of extensive dunefields. The shape and orientation of the dunefield, as well as the morphology of individual dunes, suggests that the sands were deposited under the influence of seasonal westerly winds with a slight east-northeasterly vergence, not dissimilar to the currently prevailing winds. At present, the dunes are stabilized by vegetation, and conditions during periods of activation were therefore probably more arid than those currently prevailing. The dunefields are best-developed in areas underlain by Woorinen Formation and near-surface Loxton–Parilla Sands, and deflation and recycling of these units provided the primary sediment input to the Qdu dunefields. The redness of the sand is thought to have been inherited from the pedogenic clay cutans of the Woorinen Formation.

On the accompanying 1:1 000 000 geological map, the dunefields of both Qdu and Molineaux–Lowan display a narrow linear 'mega-blowout' morphology suggesting that, unlike the Woorinen Formation, they may have migrated across country for considerable distances from west to east. Some of the Qdu dunefields, for example, appear to be anchored adjacent to the eastern side of the Darling River. The river and its narrow floodplain are entrenched within the Mallee region and could have provided several pathways for recycled Pliocene sand. Some of the sand may have been blown into the fluvio-lacustrine systems from adjacent Woorinen dunes and sand plain areas to the west, and subsequently been washed and recycled into source bordering dunes to the east of the river. These were

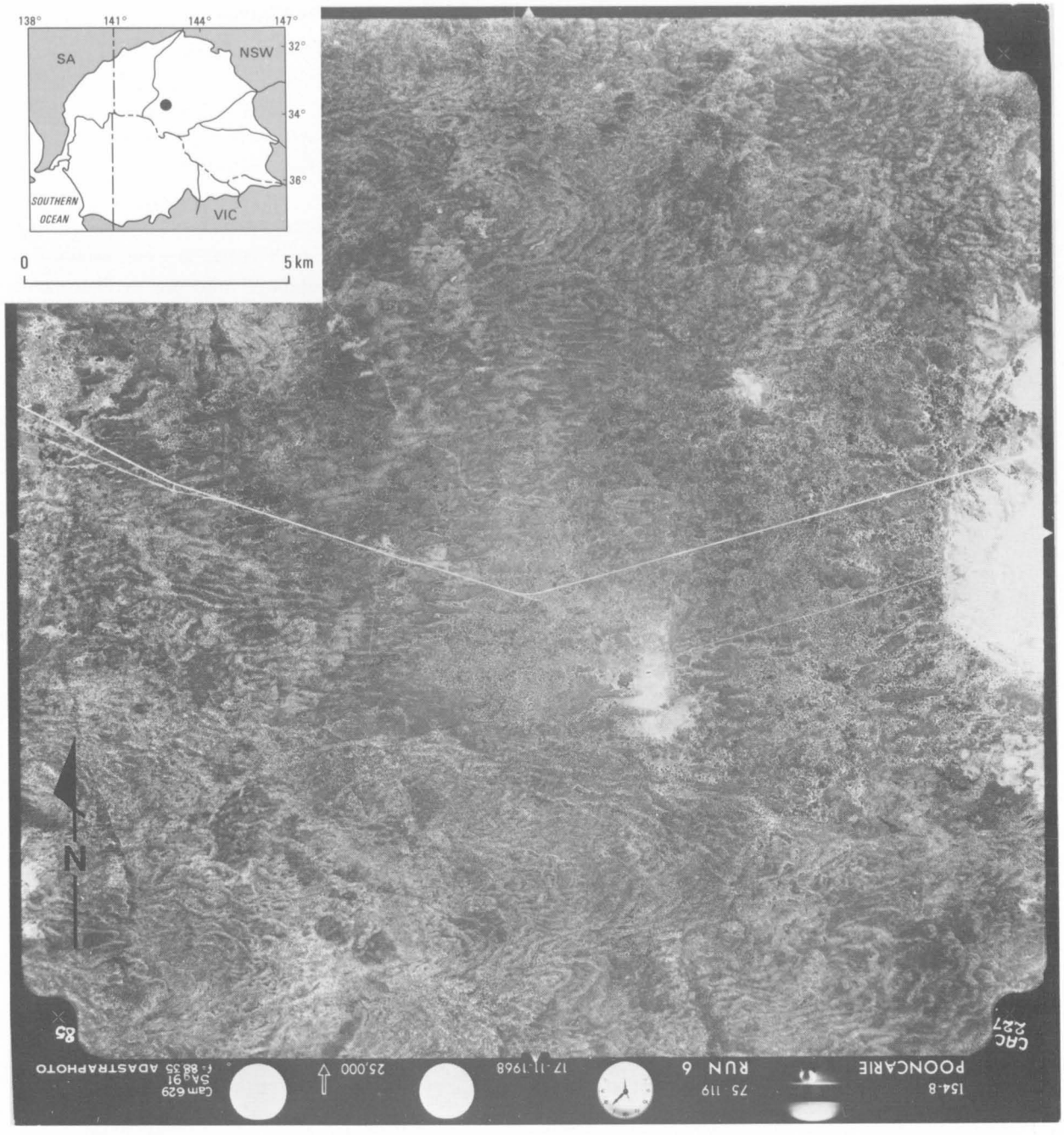


Fig. 151. Airphoto showing representative duneforms of Qdu, southeast POONCARIE; photo from National Mapping RC9 Series, Pooncarie Run 6, No. 85; photographed 17/11/1968.

then re-mobilised into Qdu dunes. Some sand may have been derived from excavation of the narrow valley of the Darling River. The eastern margins of the valley are incised below the level of the base of the Woorinen Formation, and the river is actively eroding Pliocene Loxton–Parilla Sands. A large proportion of the Qdu unit immediately to the east of the Darling River, therefore, probably consists of recycled Loxton–Parilla Sands. It also seems likely that a large component of the sand was recycled by local deflation, winnowing and remobilisation of the Woorinen Formation. The sand grains are texturally similar to those of the underlying Woorinen Formation, which itself consists of recycled Pliocene sand. With the exception of red clay cutans, the clay component of the Woorinen Formation is largely absent. Aeolian deflationary processes may have winnowed the clay component from the sand grains, and blown it for several hundreds of kilometres to the east, contributing to the layers of 'parna' dust over the Riverine Plain and adjacent highland regions.

Dunefields of Qdu sands are also developed east of the Willandra Lakes system. Bowler & Magee (1978) suggested that the addition of salts derived

from deflation of the lake floors may have activated the dunes, by accelerating the destruction of the vegetation cover over the parent Woorinen Formation. Similarly, salts derived from the Darling Anabranch lakes during past periods of aridity may have contributed to a lack of vegetation cover and to mobilisation of the dunefields in the Darling River region.

Stratigraphic nomenclature. The unit is unnamed, and is defined partly on its morphostratigraphic character and partly on its lithostratigraphic character.

Type section. No type section has been nominated. A representative type area lies east of Pooncarie, between the Darling River and Willandra Lakes system. An aerial photograph displaying the distinctive dune morphology is shown on Figure 151.

Stratigraphic relationships. The unit disconformably overlies older Pleistocene aeolian, fluvial and lacustrine units. It is partly equivalent to the youngest lunette sediments. Components of Qdu, which are mobile at the present-day, are equivalent to the Piangil Member of the Woorinen Formation. The unit is morphologically similar to, and transitional with, the aeolian dunefields of the Molineaux Formation of southeast South Australia and the Lowan Sand of northwest Victoria (unit Qdm). The main difference lies in the likely provenance of the siliceous sands. A large proportion of the red-stained Qdu sand is thought to have been derived by reworking of Woorinen Formation, whereas a greater proportion of the yellow Molineaux–Lowan Sands may have been directly derived from erosion of the underlying Loxton–Parilla Sands, particularly from the southwest of the Murray Basin. Much of the Lowan Sand, in the transitional zone of the Sunset Desert area, is virtually identical to Qdu sands farther north.

Aquifer characteristics and land management. In comparison with the clay-rich Woorinen Formation, sand of the Qdu unit is highly porous and permeable, and lacks an impermeable calcrete base. Consequently, the dunefields have proved to be unsuitable for clearance and cultivation. In addition, pastoral activities over the past century have contributed to a significant degradation of the natural vegetation cover, and may be partly responsible for recent local remobilisation of the dunes.

Data sources. Descriptions of the lithology and geomorphic character of the Qdu dunefields are contained in Bowler & Magee (1978).

Unit: Molineaux–Lowan Sands
Age: Quaternary, mainly Late Pleistocene to Holocene
Map symbol: Qdm
Associated units: Equivalent to Unnamed Quaternary aeolian dune deposits (Qdu)

Lithology. The Molineaux Sand of South Australia and the Lowan Sand of Victoria are essentially the same unit: an unconsolidated siliceous aeolian sand. Well-sorted, highly spherical quartz usually makes up more than 98% by weight of the sand, with minor tourmaline, zircon, muscovite, and iron oxide being the most common accessory minerals. Frosted quartz grains are locally covered with iron oxide, and soft columnar carbonate nodules are present in places. The Molineaux–Lowan Sands are commonly yellow, fine to medium-grained, and characterised by low kurtosis and positive skewness (Lawrence, 1966).

Distribution and thickness. The distribution of the Molineaux–Lowan Sands is shown in Figure 130. These sands form extensive dune fields in the western Murray Basin, including the Sunset Desert, Big Desert, and Little Desert in western Victoria (Fig. 14). In South Australia, the Molineaux Sand is up to 20 m thick, with thicknesses of 6–9 m being more typical. It also veneers old erosion surfaces with local relief of 30 m or more (Firman, 1972; Rogers, 1980a). In Victoria, the equivalent Lowan Sand also has a maximum thickness of 20 m, but most dunes are less than 9 m high (Lawrence, 1976a, 1988a).

Geometry, topography, and vegetation. The Molineaux–Lowan Sands form extensive tongue-shaped dune fields in the western Murray Basin (see Fig. 132). These have the appearance of mega-blowouts, with sand movement towards the east.

In Victoria, the Lowan Sand characteristically occurs as extensive dune fields and sand plains (see Fig. 131; Lawrence, 1976a, 1988a). Hills (1939), Lawrence (1966), and Bowler & Magee (1978) grouped these dunes together as 'jumbled or irregular'; Lawrence (1980) later sub-divided the Lowan Sand into three main types. These are 'parabolic dune chain patterns, a pattern of densely packed low longitudinal dunes of the tear-drop type, and sand plains with sparse dunes'. The parabolic dunes are oriented WSW–ENE, are from 5–15 m high, and most commonly occur in chains; the nose is in some cases blunt, terminating in a slip face, whilst in others it has been partly blown out to form a seif dune of the tear-drop type. The tear-drop dunes are commonly closely packed and less than 10 m high,

with a dominant east–west orientation; they are asymmetrical in profile, with a steeper northern face (Lawrence, 1980). In South Australia, the Molineaux Sand was described by Firman (1973, p.56) as occurring as "longitudinal dunes trending west–east, and northwest–southeast, as jumbled (parabolic) dunes, or as a capping on Woorinen Formation".

Where the natural vegetation has been cleared, the Molineaux–Lowan Sands are highly mobile. Soils are poorly developed within these dunes, vegetation is sparse and restricted to tall and low shrubs, and tussock and hummock grasses.

Stratigraphic relationships. The Molineaux–Lowan Sands overlie a multitude of older units, including the Murray Group limestones. The unit also overlies the Loxton–Parilla Sands, Bridgewater and Padthaway Formations, unnamed lagoonal unit Qpu, Blanchetown Clay, Shepparton Formation, unnamed sand plains (Qdp), Woorinen Formation, and various calcretes. Molineaux–Lowan Sands also overlie and interfinger with Yamba Formation (Qly), and other lacustrine sediments (Ql); they interfinger with the Pooraka and St. Kilda Formations, and with minor modern alluvium (Qa). Modern alluvium also locally overlies the Molineaux–Lowan Sands, and minor modern lacustrine sediments (Ql, Qly) and associated lunettes (Qdl) are incised within it.

Age evidence. The Molineaux–Lowan Sands contain some Aboriginal artifacts, but no fauna has been systematically described. The sand is only locally mobile at present, but the facts that it has no well-developed calcretes, and only minor local alluvium overlies it, suggest a relatively young age. Lawrence (1976a, 1980, 1988a) suggested that the Lowan Sand ranged through most of the Quaternary, whilst Firman (1973) described the Molineaux Sand as Recent. The two units are not entirely equivalent (see 'Woorinen Formation' and below). The Molineaux Sand postdates most of the Woorinen, and the Bridgewater Formations, which it locally overlies (Firman, 1973). It is certainly no older than Late Pleistocene; in the southwest its sediments are at least partially derived from the Loxton–Parilla Sands as well as the Woorinen Formation and the Bridgewater Formation. Gardner & others (1987) obtained thermoluminescence ages of Holocene (8000 $\pm$ 1900 yrs. B.P.) and Late Pleistocene (34 500 $\pm$ 5000 yrs. B.P.).

Characteristics and environment of deposition. The Molineaux–Lowan Sands are characterised by lithology, geomorphic expression, and stratigraphic position. They are similar to reworked sand dunes of the Woorinen Formation (Qdu), but can be distinguished from them by lithology and geomorphic expression. The Molineaux Sand is similar to the Bunyip Sand, but the latter is restricted to fluvial-derived dunes adjacent to the modern Murray River (and hence has a different origin from that of the Molineaux–Lowan Sands).

The Molineaux–Lowan Sands were deposited and are being reworked in an aeolian environment, although there has been some debate about the source of sediment. Hills (1939) and Lawrence (1966) considered the Lowan Sand to be derived by aeolian erosion of the underlying Parilla Sand, and not, as suggested by Crocker (1946) and Sprigg (1952a), by stripping, during an arid phase, of the quartzose 'A' horizon developed on the calcareous coastal dunes of the Bridgewater Formation. Firman (1973) thought that Molineaux Sand was derived from either the Loxton Sands, the Parilla Sand, or from aeolianite (Bridgewater Formation) exposed by erosion; he also pointed out that the Molineaux Sand has been developed partly from the underlying Woorinen Formation. It seems probable that the sand is derived from multiple sources, but that much was originally derived from the Loxton–Parilla Sands, and some was reworked via older Quaternary units. In coastal areas the primary source appears to have been the Bridgewater Formation.

Stratigraphic nomenclature. The Molineaux Sand is named after the Hundred of Molineaux, County Buccleuch, South Australia (Firman, 1973). The Lowan Sand is named after County Lowan, Victoria (Lawrence, 1966).

Type localities. Firman (1973) defined the type localities of the Molineaux Sand as shown on his Pinnaroo–Karoonda maps (Firman, 1965b, 1966b); these cover parts of PINNAROO. Lowan Sand in Victoria is typified by that in the Big and Little Deserts (Lawrence, 1966).

Correlations. The Molineaux Sand of South Australia is equivalent to the Lowan Sand plus the Piangil Member of the Woorinen Formation (mobile sand) in Victoria. The Woorinen Formation is also recognised in South Australia, but the Piangil Member is included in Molineaux Sand. Molineaux–Lowan Sands are partly time equivalent to the Bunyip Sand in South Australia, and to remobilised Woorinen Formation (Qdu) in New South Wales.

Hydrogeology and land use. The Molineaux–Lowan Sands are highly porous, and recharge underlying aquifer systems. The highly unstable dune fields are relatively unsuitable for agriculture in most locations; however, South Australia has a higher density of

farming within these dune areas than does Victoria. The differences in land use between the states can readily be seen on aerial photographs and on Landsat mosaics (see Fig. 5). The more mobile areas of both the Molineaux Sand and Lowan Sand have been designated as wildlife reserves and national parks.

Remarks. The aeolian sands which form the dunefields of Molineaux–Lowan Sands are morphologically similar to — and transitional with — the unnamed Qdu dune deposits. In southern areas they are lithologically distinct, reflecting differences in provenance of sand material, whereas in the Sunset Country they are lithologicaly similar (see 'Qdu').

Data sources. The Molineaux–Lowan Sands are described in Hills (1939), Crocker (1946), Sprigg (1952a), Rowan & Downes (1963), Firman (1965b, 1966b, 1972, 1973), Lawrence (1966, 1976a, 1980, 1988a), Bowler & Magee (1978), and Rogers (1980a).

Unit: Unnamed Quaternary fluvial-derived, aeolian, source-bordering dune deposits
Age: Quaternary, mainly Late Pleistocene to Holocene
Map symbol: Qad
Component unit: Cobram Sand
Associated unit: Bunyip Sand (Table 38)

Lithology. Fluvial-derived, aeolian, source-bordering dunes consist of unconsolidated, yellow to pale-orange or red, quartz sand, with locally abundant mica and lithic clasts. The sand grains consist mainly of quartz, but are lithologically more diverse than other dune deposits, and include feldspar and clasts of slate, chert, and quartz sandstone. They are also chemically and texturally immature in comparison with other dune deposits. Minor soft and fragile calcareous rhizoliths are locally exposed in recently eroded deflation hollows. Soils are not well developed over recently active dunes adjacent to modern river channels, but dunes adjacent to inactive river channels and elevated stranded dunes are usually mantled by a red-brown soil (Baldwin & others, 1939; Butler & others, 1942; Skene & Poutsma, 1962). In general, however, the unit is only weakly modified by pedogenesis and intrusion of root systems. Consequently, internal structures in the form of high-angle cross-beds and well-defined lamination planes are well preserved. Younger components are yellow or pale-red, in comparison with older components which are red and are characterised by an increasing content of red clay.

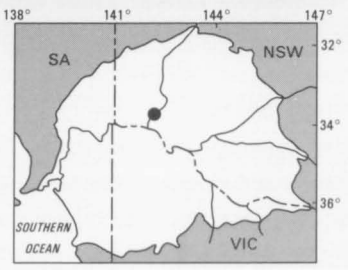


Fig. 152. Mobile dune — part of source-bordering dune complex, east of, and adjacent to, Darling River (southeast ANABRANCH).

Distribution and thickness. Small source-bordering dunes and dunefields are associated with both active and inactive river channels throughout the Riverine Plain, and also with the entrenched floodplains of the Murray and Darling Rivers, and the Darling Anabranch.

Outcrop and geomorphic expression. Source-bordering dunes form strings of low sand hills and elongate hummocky dunefields, located adjacent to present-day and former river channels. The sand bodies range in size from a few hundred square metres to small dunefields extending over several square kilometres. Small dunefields have developed adjacent to active or former point-bar and scroll-bar complexes, particularly where these are perpendicular to the dominant wind direction. For example, a number of small dunefields, consisting of east–west oriented dunes, are located east of the Darling River. Elsewhere, over parts of the Riverine Plain, elongate hummocky sand hills have developed parallel to stranded and re-worked channel sands of the 'prior streams' of the Shepparton Formation. Within the dunefields, individual dunes form low elongate elliptical mounds, which together can locally accumulate as sand hills up to 20 m high. Some dunes, adjacent to point-bar complexes in fluvial channels, have a rounded hummocky crescentic morphology.

Most dunes have been stabilised by vegetation, but some have been stripped of vegetation, in some cases by over-grazing, and older components have been extensively eroded, leaving deflation hollows. These are partly blanketed by low hummocky drifts

TABLE 38. UPPER PLEISTOCENE – HOLOCENE BUNYIP SAND

Unit: Bunyip Sand

Age: Quaternary, probably entirely Holocene

Map symbol: Qdb

Associated unit: Undifferentiated fluvial-derived, aeolian, source-bordering dune deposits (Qad)

Lithology. Light-red to brown, unconsolidated, quartz sand. Quartz grains well-sorted, locally iron-stained with red clay ctans. Firman (1972) recognized two phases: older, darker phase locally with soft calcareous pipes or nodules, and younger more mobile phase with lower carbonate content, restricted to minor calcareous rhizoliths.
Distribution and thickness. Adjacent to east bank of Murray River in RENMARK (Fig. 153). Takes form of elongate blowout dunefields of variable thickness (max. 5 m; Firman, 1972, 1973). Rogers (1978) included veneers of reworked Woorinen Formation on CHOWILLA in Bunyip Sand; included in Qdu on enclosed 1:1 000 000 map.
Topography and vegetation. Forms elongate, tongue-shaped dunefields, slightly higher than adjacent flat calcrete plains (Figs 153, 154, 155). Individual dunes vary in shape, from sub-parabolic through irregular to linear, but main direction of dune migration invariably towards east – northeast. Locally forms veneer less than 1 m thick over older units. Prior to European settlement stabilised by Mallee vegetation – clearing destabilised dunes and caused salinisation of near surface aquifers. Dunes mobile at present; vegetation restricted to few hardy tussock grasses and shrubs; many dunes deflated and almost entirely unvegetated.
Palaeontology and age evidence. Only fossilized material recorded from Bunyip Sand is anthropogenic: i.e. aboriginal middens and other artefacts (Firman, 1972). Some material carbon dated at few thousand years B.P., but accurate lower age for Bunyip Sand not known; probably post-dates last glacial maximum at about 17–18 000 yrs. B.P., when Murray Gorge actively eroded. Present-day deflation and reworking enhanced by clearance of vegetation.
Characteristics. Lithology, geographic location, and physiographic expression.
Environment of deposition. Derived from fluvial sands within Murray Gorge, blown out of valley by prevailing westerly to southerly winds (Fig. 11), and deposited as dunes on cliff tops. Dunes progressively migrated to east under influence of same prevailing winds (Fig. 155). Very well-sorted nature of Bunyip Sand indicates finer fluvial-derived material blown beyond immediate cliff top environment, and presumably deposited as thin layer of loess or parna farther east. Firman (1972) attributed formation of Bunyip Sand to reworking of Woorinen Formation sand, some of which has undoubtedly blown into Murray valley from west, been reworked, and blown out to east – process probably operates east of North West Bend (Fig. 153); on other hand, no Woorinen Formation west of Murray River, south of North West Bend (Fig. 130), and Bunyip Sand here derived from river sand. Each of four Bunyip Sand dunefields south of North West Bend associated with bend in Murray Gorge, where river floodplain changes direction from southeast to SW (Fig. 153) – these bends act as funnel for prevailing westerly to southerly winds, resulting in deflation of point-bars and deposition of Bunyip Sand as 'source-bordering' dunes to northeast of valley (Fig. 155).
Stratigraphic nomenclature and type section. Named by Firman (1966c) after Bunyip Reach of Murray River, near Chowilla Homestead, County Hamley, S.A.; very small area of Bunyip Sand occurs on east bank of river at this reach, but main occurrences between Blanchetown and Waikerie (Fig. 153). No formal type section; Firman (1973) designated outcrop on RENMARK as type localities (Firman, 1972).
Stratigraphic relationships. Overlies several older units, including Woorinen Formation, calcretes, Blanchetown Clay, Bungunnia Limestone, Loxton–Parilla Sands, Norwest Bend Formation, and Morgan Limestone. One of youngest geological units in Murray Basin, and neither interfingers with, nor underlies, any other formation.
Correlations. Similar environment of deposition to many source-bordering dunes within Riverine Plain. Postdates main periods of lunette formation in west Murray Basin, but can be considered to be part time-equivalent to uppermost, remobilized, parts of Molineaux–Lowan Sands; also time-equivalent to sediment of modern Murray and Darling River valleys.
Hydrogeology. Above regional groundwater table; locally acts as recharge area for underlying Murray Group aquifer system.
Remarks. Not fundamentally different (except for much greater extent) from fluvial-derived source bordering dunes adjacent to streams of Riverine Plain; notable in that its distribution can be closely related to changes in direction of Murray Gorge.
Data sources. Firman (1966c, 1972, 1973, 1985), Rogers (1978).

of loose sand, flanked by high, steep-sided, dunes with rippled surfaces, which are currently advancing over adjacent vegetation (Fig. 152). Some of the small source-bordering dune complexes adjacent to the modern Darling River, for example, have been extensively deflated and locally mobilised into small easterly trending blow-out dunefields.

Palaeontology. Older components of the unit contain marsupial remains and Aboriginal artifacts. Stone-scraping implements, shellfish middens and fireplace stones have accumulated in some deflation hollows. McIntyre (1981) described the fossil remains of *Phascolonus sp.*, an extinct Pleistocene giant wombat, from a source-bordering dune adjacent to the lower Darling River. Hope & Jacobs (1982) noted that archaeological sites are preferentially preserved in source-bordering dunes.

Age evidence. The unit is confined in distribution to the surface, and is mainly of Late Pleistocene to Holocene age. A Late Pleistocene age is indicated by the association with the inactive 'prior' and 'ancestral' stream channel traces preserved at the surface of the Riverine Plain within the upper Shepparton Formation and younger Coonambidgal Formation. A Holocene age is indicated in a few areas where dunes overlie sediments of the Coonambidgal Formation, and are actively mobile adjacent to present-day river channels. Most of the dune deposits on the Riverine Plain are, however, stabilised at the present-day and were deposited during Late Pleistocene periods when the large wavelength channels of the prior streams carried a seasonal bed-load of coarse sediment. Material from Aboriginal middens within source-bordering dunes adjacent to Talyawalka Creek (MANARA) and Tandou Creek (MENINDEE) yielded radiocarbon age determinations of between 9000 and 15 000 yrs. B.P. (Hope & Jacobs, 1982). Based on radiocarbon age determinations, Bowler (1978a) indicated that formation of the dunes in the southern Riverine Plain largely ceased after 13 000 to 16 000 yrs. B.P. This is thought to have accompanied a switch from bed-load dominated streams to suspended load streams.

Interpretation of environment of deposition. As im-

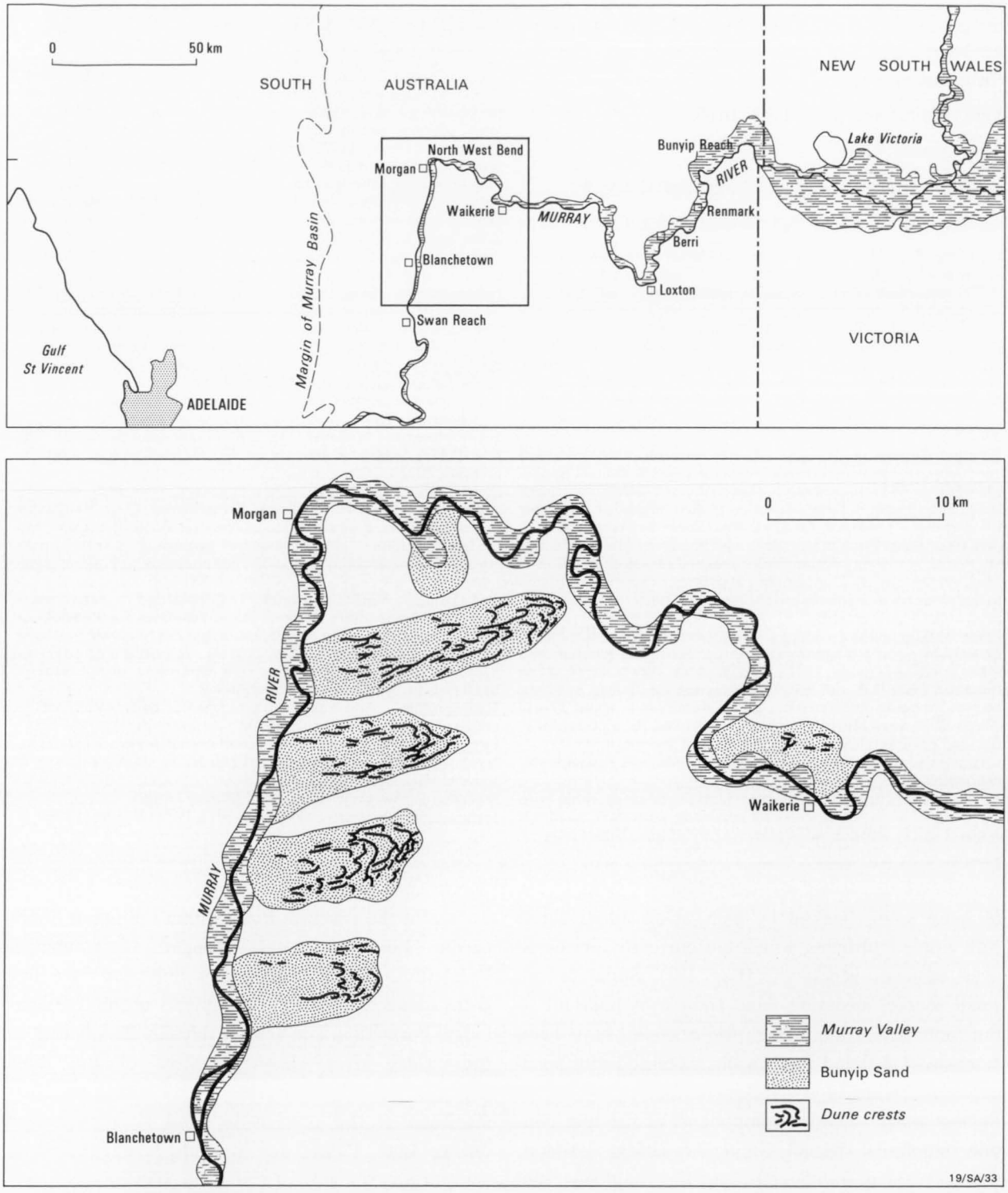


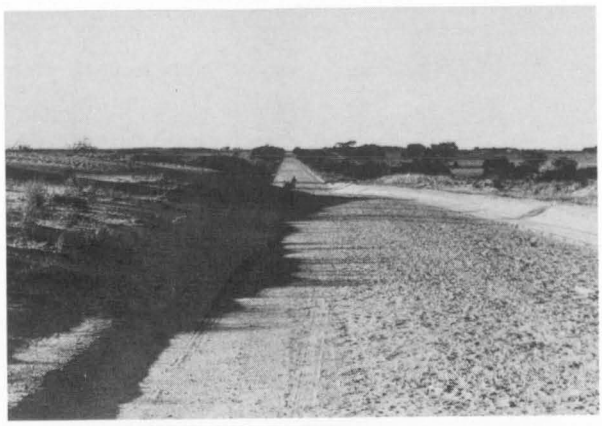
Fig. 153. Distribution of Bunyip Sand, western Murray Basin – based on Firman (1972).

plied by its descriptive name, the unit was deposited in an aeolian environment bordering a local source of sediment. The accumulation of these deposits can therefore be related to an interplay between fluvial and aeolian processes. Source-bordering dunefields are particularly well-developed on the leeward side of fluvial point-bars and scroll-bar complexes within meander belts. Other deposits are associated with elongate channel sands originally deposited in anastomosing distributaries. These were also deflated by wind erosion and the resulting sand heaped into elongate dune deposits. The local provenance of the sand explains some of the diverse assemblages of micaceous and lithic clasts atypical of other well-sorted aeolian sediments of the basin.

As noted previously, some authors have suggested that the sand-dominated fluvial 'prior stream' channels functioned during pluvial periods, whereas

others have suggested they operated during arid-phase floods, when sediment was readily available owing to a lack of vegetation cover, particularly in the adjacent highland areas (see 'Shepparton Formation'). The association with the source-bordering dunes tends to support the later arid-phase view. Source-bordering dunes were particularly active adjacent to bed-load dominated channels. Bowler (1978a) suggested that this activity correlated with periods of glacial/periglacial conditions in the adjacent highlands, when sediment input to the rivers was seasonally high (accompanying spring meltwaters), vegetation cover was depleted, and sandy point-bars and channel sands were subject to deflation during seasonal periods of low flow.

Stratigraphic nomenclature and type section. The unit has not been named or defined as a lithostratigraphic unit, because it has been identified mainly using morphostratigraphic criteria, although variants of the unit, such as the Cobram Sand and the Bunyip Sand (Qdb – Table 38) have been locally named and defined. The Cobram Sand, for example, was named by Lawrence (1975) after the small town of Cobram in JERILDERIE. No type section has been nominated for Qad, but the type section of the Cobram Sand is located in a sand and gravel pit 6.5 km southeast of Cobram.



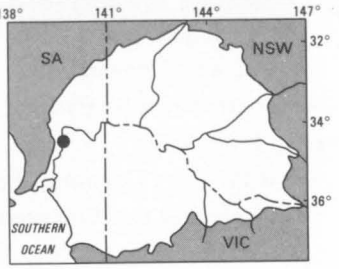


Fig. 154. Mobile dune of Bunyip Sand advancing over road (from left to right), east of Murray River Gorge (RENMARK).

Stratigraphic relationships and characteristics. The source-bordering dunes form a morphostratigraphic unit, which is identified mainly on the basis of geomorphic expression and its association with fluvial

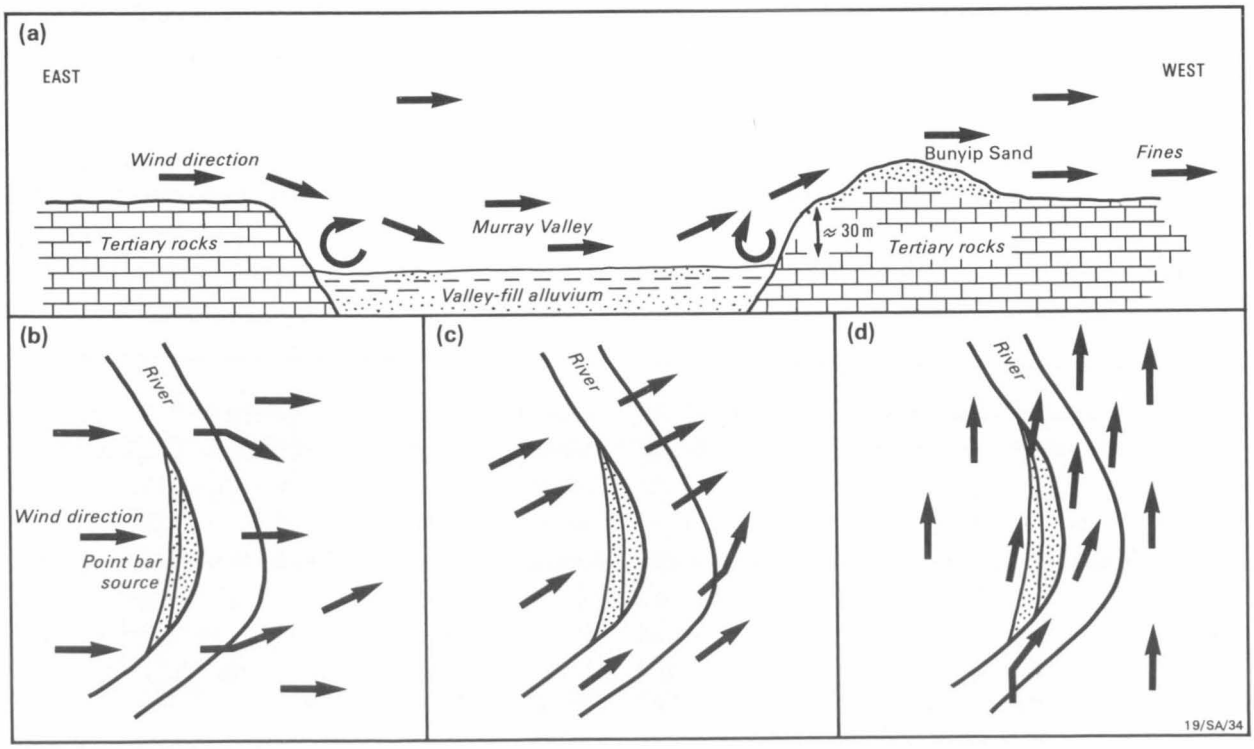


Fig. 155. Deposition of Bunyip Sand: (a) sediment within valley picked up by prevailing winds; sand dropped on cliff tops, fines carried farther east; orientation of valley causes funneling effects under (b) westerly, (c) southwesterly, and (d) southerly wind regimes – controlling deposition and accumulation of Bunyip Sand; sand from river bends blown northeast.

channel deposits of the Shepparton and Coonambidgal Formations. In addition, many source-bordering dunes are lithologically diverse in comparison with the well-sorted sands of conventional dunefields. Equivalent sediments possibly occur in the near-surface but have not been identified.

Data sources. Butler & others (1973) mapped the distribution of source-bordering dunes of the Riverine Plain. Descriptions of source-bordering dunes are also provided in Lawrence (1975, 1976a, 1988a) and Bowler (1978a).

Unit: Coonambidgal Formation of the Wunghnu Group and other undifferentiated alluvial deposits
Age: Late Pleistocene to Holocene
Map symbol: Qa
Synonyms: The Coonambidgal Formation is equivalent to the 'Coonambidgal' of Butler (1958) and includes the 'Ancestral Streams' of Pels (1964b, 1966), Kotupna Complex and Goulburn Complex of Bowler (1978a)
Associated units: Undifferentiated Upper Pleistocene to Holocene alluvial deposits of the modern river systems in and around the Murray Basin have been included in 'Qa' on the accompanying 1:1 000 000 scale geological map. These include the MONOMAN Formation (Table 39)

Lithology. The Coonambidgal Formation consists predominantly of unconsolidated, grey, red-brown, silt, silty clay, sand and gravel. Most of the sand and gravel are poorly sorted, consisting of a polymictic assemblage of quartz and lithic clasts, and are normally micaceous; minor channel sands consist of relatively well-sorted quartz grains. The silt and clay are generally unweathered except for the upper surface of older components of the unit where grey soils and minimal red-brown earths are developed. In highland valleys the gravel includes cobbles and boulders.

Distribution and thickness. Extensive deposits of Coonambidgal Formation and other Upper Pleistocene to Holocene alluvial deposits are found within the confined floodplains of modern river systems in the Riverine Plain in the east (e.g. Figs 108, 111), and the Murray–Darling River system in the west (Fig. 156). Further alluvial deposits are preserved in tributary highland valleys – particularly in those flanking the southern and eastern margins of the basin. Upper Quaternary alluvial sediments are also found around the southern margin of the basin, and extend to the north in inter-ridge corridors between stranded ridges of Pliocene Loxton–Parilla Sands and Quaternary Bridgewater Formation. Additional minor deposits of 'Qa' alluvium occur within the aeolian Mallee terrain. These include the deposits of streams which terminate within the aeolian landscape, as well as relict traces of former drainage systems and small local basins of internal drainage.

In the Riverine Plain, extensive deposits of Coonambidgal Formation are associated with the Lachlan, Murrumbidgee, Murray, Ovens, Goulburn, Campaspe and Loddon River systems. A network of interconnected distributary channels extends throughout the flat-lying plain and coalesces towards its central western margin. Some channels are small, others large, and some are permanently flowing, whereas others are ephemeral and carry only floodwaters. The distributary channels of some rivers are separated from the main channel by several tens of kilometres, and some channels merge with the distributary channels of an entirely different river. In places where anastomosing distributary channels are particularly concentrated, inliers of Shepparton Formation form chains of elongate, oval-shaped stranded terraces within a channeled plain of Qa. These are particularly well-developed, for example, in the lower Loddon, lower Goulburn and parts of the Murray River systems of the southeast Riverine Plain. An extensive area of Coonambidgal Formation occurs east of the Cadell Fault in a triangular area of 1800 km^2 of ponded drainage between Echuca, Deniliquin and Tocumwal. Other extensive areas of Coonambidgal Formation occur near the confluence of the Murray and Murrumbidgee Rivers, and the confluence of the Lachlan and Murrumbidgee Rivers, where Coonambidgal Formation sediments extend over a large area of low-lying floodplain and swamp up to 55 km in width.

The thickness of the unit is variable. Channel sands that have been investigated beneath the Riverine Plain are up to 20 m thick. Geological sections across the Murray River Gorge indicate that fine-grained 'Qa' sediments of the Coonambidgal Formation are at least 15 to 25 m thick, and underlying coarse-grained 'Qa' sediments assigned to the Monoman Formation (Table 39) are a further 20 to 25 m thick (Figs 87, 157; Ludbrook, 1958b, 1960; Gibson, 1959; Johnson & others, 1960; Lindsay, 1967b; Steel, 1967; Firman, 1973; Twidale & others, 1978).

Outcrop and geomorphic expression. The Coonambidgal Formation is locally exposed in river cliff sections on meander bends and in minor sand and gravel pits. The unit occurs in confined floodplains

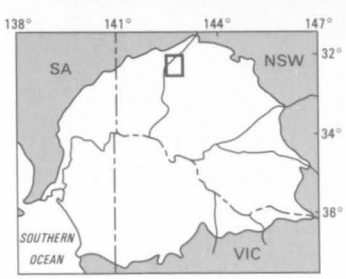


Fig. 156. Photomosaic of Nartooka 1:100 000 Sheet area, showing aeolian-modified floodplain of Darling River, entrenched within aeolian landforms of northern Murray Basin.

TABLE 39. UPPER PLEISTOCENE – HOLOCENE MONOMAN FORMATION (part of Qa)

Unit: Monoman Formation

Age: Late Pleistocene to ?Early Holocene

Map symbol: included in Qa

Lithology, distribution and thickness. Predominantly coarse-grained quartz sand, gravel; minor silt, clay. Forms lower layer of concealed 'valley-fill' beneath confined floodplain within Murray River Gorge in S.A. (Fig. 157). Approx. 20 – 25 m thick (e.g. Chowilla damsite; Fig. 87; Firman, 1973), although thickness of 40 m recorded on fig. 2 of Twidale & others (1978). Entirely concealed and encountered only in boreholes.

Palaeontology and age evidence. Fossil wood; Marshall (1973) identified extinct Late Pleistocene marsupials, including giant wombat Phascolonus cf. P.gigas and Macropus ferragus towards base near type area. At same locality, Gill (1973a) obtained radiocarbon age of 7200 ± 140 yrs. B.P. from log of Eucalyptus largiflorens from upper part of unit. Post-dates Blanchetown Clay and truncates older Quaternary alluvial deposits. Recent age suggested by Firman (1973), although age of basal components uncertain, and presence of extinct giant marsupial remains indicates includes Late Pleistocene sediments.

Environment of deposition. Fluvial environment; may have been partly derived from reworked Loxton – Parilla Sands (Firman, 1973). Base extends well below present-day sea-level and Gill (1973a), Twidale & others (1978) related incision of Murray River Gorge to series of glacio-eustatic lowerings of sea-level, after uplift of Pinnaroo Block – suggested deposition of Monoman Formation accompanied post-glacial rise in base-level, 17 000 – 6000 yrs. B.P.

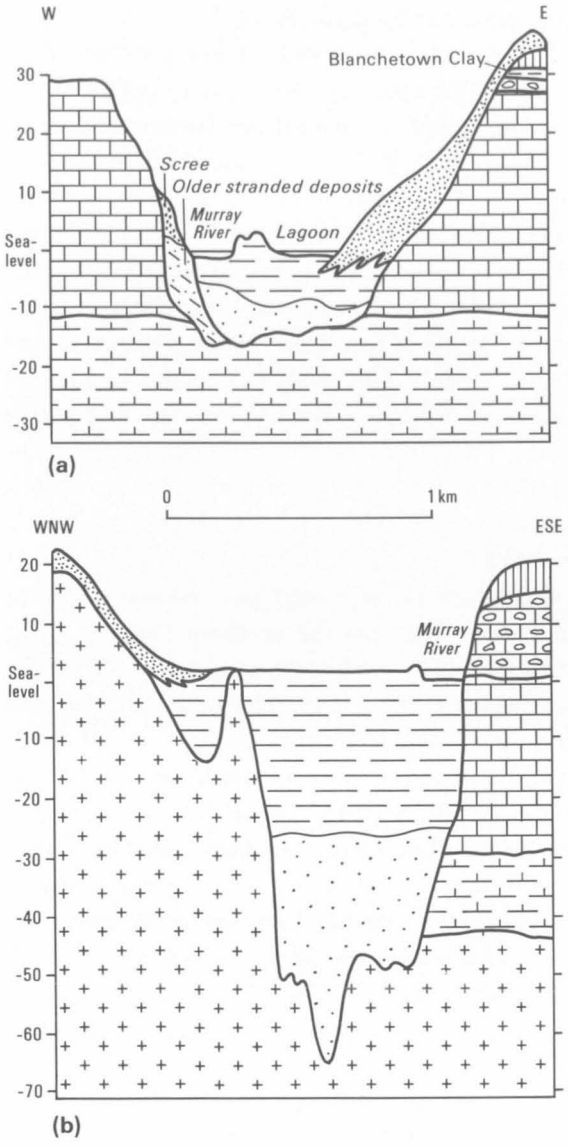
Stratigraphic nomenclature and type section. Named by Firman (1966c), after Monoman Creek, near Chowilla (southeast CHOWILLA). Borehole section on line 'D' at proposed Chowilla damsite nominated as type section (Firman, 1966c, 1967b); material from type section held by SADME.

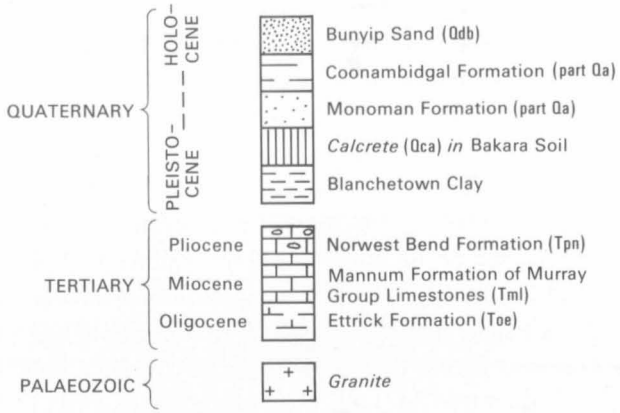
Stratigraphic relationships. Firman (1971b, 1973) in S.A., and Gill (1973a) in NW Victoria, differentiated Monoman Formation sequence of coarse sand and gravel from Coonambidgal Formation. Gill (1973a) suggested disconformity separates Monoman Formation from Coonambidgal Formation – based on presence of fossil tree material and oxidised surface between two units. Equivalents elsewhere in basin included in Coonambidgal Formation or upper Shepparton Formation. Relatively young radiocarbon date obtained by Gill (1973a – see above) suggests correlation with Coonambidgal Formation of Riverine Plain farther east – based on lithology and Late Pleistocene age of extinct marsupial fauna (Marshall, 1973), unit can be partly correlated with sand-dominated Kotupna Complex (Coonambidgal Formation) of Bowler (1978a), although, given uncertainties of age of basal components, it could also partly correlate with components of Shepparton Formation. Unconformably entrenched within older stranded Quaternary alluvial sediments, Loxton – Parilla Sands, Bookpurnong beds, and limestone formations of Murray Group.

Data sources. Firman (1966b, 1967b, 1971b, 1973), Gill (1973a), Marshall (1973), and Twidale & others (1978).

incised within older fluvial and aeolian landscapes. The surface geomorphology of the Riverine Plain is described in Chapter 3. Within the Riverine Plain the modern rivers form narrow meander belts and anastomosing distributary channels. The meander belts are associated with narrow floodplains inset within a number of terraces 1.5 to 5 m below the general level of the Riverine Plain. The confined floodplains range in width from a few hundred metres up to several kilometres. Locally, in areas where anastomosing distributary channels converge, the area underlain by Coonambidgal Formation can be 10 to 30 km wide, and east of the Cadell Fault is 60 km wide (see Fig. 16). The Riverine Plain is characterised by extremely low gradients, and consequently the main channels of the river systems are sluggish and slow-moving except during periods of flood. As a consequence, much of the area underlain by 'Qa' sediments is subject to flooding and on aerial photographs can be seen to be characteristically covered by dense woodland, swamp forest, and shrub vegetation. The lower levels of the floodplains are traversed by numerous ephemeral and abandoned channels, billabongs and traces of stranded former scroll bars (Fig. 158). Numerous small swamps occur in areas of poorly organised drainage within the modern floodplains. The Booligal swamps of the lower Lachlan, and the Great Cumbung Swamp at the confluence of the Lachlan and Murrumbidgee Rivers extend over large areas.

The modern fluvial channels of the Riverine Plain are highly sinuous. As noted previously (see 'Shepparton Formation'), a range of channel styles occurs, but two types of 'end-member' abandoned river channels are dominant, particularly in the southeast. These consist of recently abandoned alluvial channels associated with higher terrace levels (Butler, 1960; 'Ancestral Streams' of Pels, 1964b), which consist of sediments of the Coonambidgal Formation, and older abandoned channels of the Shepparton Formation ('Prior Streams' of Butler, 1950; Figs 108, 109, 110). The distribution of the ancestral streams is generally closely associated with that of the present-day rivers, and the former channels often carry water during periods of flood. As discussed by Schumm (1968a), the meander patterns of the stranded ancestral channels of the Murrumbidgee River system, resemble those of the sinuous modern river systems, but are of much greater size. In contrast, the prior stream channels are relatively straight, wide and shallow, but are similar in size to the ancestral stream channels. Many ancestral channels were thought to have carried a suspended load of sediment, similar to that of the modern rivers, rather than the coarse bed-load characteristic of the prior streams. In detail, however, as described by Bowler (1978a), parts of the ancestral system also carried a sandy bed-load, reflecting variations in climatic conditions in catchment areas. In the floodplain of the Goulburn River, at the southeastern margin of the Riverine Plain, for example, differences in channel morphology were first noted by





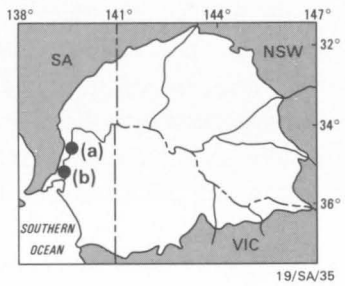


Fig. 157. Geologic sections across Murray River Gorge: (a) 3–4 km south of Swan Reach; (b) 5 km southeast of Murray Bridge at Monteith bridge site; based on Twidale & others (1978), with data from Ludbrook (1958b), Gibson (1959), Steel (1967), Lindsay (1967b), and Firman (1973).

Gregory (1903). Lawrence (1976a, 1988a) recognised two sets of inset terraces, and observed that meander lengths are greater in the higher (older) terrace. Pels (1971) described a number of ancestral phases, and Bowler (1978a) subsequently recognised at least three phases of channel development associated with the modern and ancestral Goulburn River (Green Gully/Tallygaroopna Complex, Kotupna Complex and Goulburn Complex; see Fig. 111). The channels of the two older complexes are characterised by coarse bed-load sandy sediments, and only the youngest Goulburn Complex is characterised by fine-grained suspended load sedimentation.

Internal geometry. Pels (1966) examined profiles of channels of Coonambidgal Formation, which were found to consist of linear sand and clay bodies up to 20 m thick. Individual sand bodies show upward-fining grain profiles, with coarse-grained sand and gravel at the base grading up into silty sand and silty clay. The modern river channels are deeply incised into the Shepparton Formation (Butler & others, 1973) and are narrow in cross-section with steep banks. Schumm (1968a) provided details of the morphology of individual channels associated with modern and ancestral channels of the Murrumbidgee River west of Narrandera. The ancestral channel complexes average about 14 km in width and have a high sinuosity ratio of 1.7 (ratio of channel to valley length over a given distance). The modern channel complex of the Murrumbidgee at Darlington Point is 6.7 km wide and also has a sinuosity of 1.7. The gradient of the modern channel is calculated at 12 cm/km, whereas that of the ancestral channel was calculated at 15 cm/km (for comparison the gradient of prior streams was calculated at 38 cm/km).

Palaeontology. The unit contains fossil wood debris and the remains of freshwater mussels. Middens with shell debris, some with fish bones and marsupial remains, can be found along the banks of most modern river channels.

Age evidence. The Coonambidgal Formation occurs at the surface of the basin and includes the sediment of modern river channels. Radiocarbon age determinations from ancestral channels, in Pels (1969b), ranged from 4200 to 30 000 yrs. B.P. At Chowilla damsite near the tri-State border in South Australia, Firman (1967b) reported a radiometric age determination of 4080 $\pm$ 100 years B.P. from fossil wood near the base of the upper valley-fill (Coonambidgal Formation). A C^{14} age determination from a shell in the 'Tartangan beds' (equivalent to Coonambidgal Formation) gave a date of 6020 $\pm$ 150 yrs. B.P. The unit is therefore of Late Pleistocene to Holocene age.

Characteristics. The Coonambidgal Formation is a geomorphologically distinct unit which is mainly incised within older deposits of Shepparton Formation. The unit underlies areas subject to periodic flooding and is commonly vegetated by a distinctive cover of forest. The modern fluvial channels are relatively small in comparison with prior and ancestral stream channels. Over much of the Riverine Plain, the younger Coonambidgal channels contain finer-grained sediments in comparison with those of the prior streams, although some ancestral channels also have bed-load sands (e.g. Kotupna Complex of Bowler, 1978a). Also, in contrast to the mottled clay of the Shepparton Formation, well-developed red palaeosols are generally lacking in the unweathered clay, sand and silt of the Coonambidgal Formation.

Interpretation of environment of deposition. The surface geomorphic expression, lithology and geometry of the sediments of the Coonambidgal Formation indicate that deposition occurred in fluvial and fluvio-lacustrine, channel and floodplain environments of existing and recently active rivers of the Murray Basin. Sedimentation is confined to floodplains eroded into older landforms, and the configuration of the floodplain deposits is partly controlled by the morphology of the landscapes within which the Coonambidgal sediments are incised. Lawrence (1976a, 1988a), for example, noted that in places the 'Qa' deposits are confined within topographically depressed channels by levees associated with the older channels of the Shepparton Formation. Similarly, at the southern margin of the undulating Mallee Plain the distribution of Coonambidgal Formation has been controlled by the morphology of underlying and flanking ridges of former strand lines of Pliocene Loxton–Parilla Sands. In South Australia, fluvial sedimentation is confined largely to the Murray River Gorge, which is incised into Miocene limestones exposed by erosion of the up-faulted Pinnaroo Block.

The fluvial channel distribution patterns of the Riverine Plain have also been partly influenced by the configuration of underlying basement features (see 'Structure'). Recent movement on pre-existing faults has locally contributed to deposition of the Coonambidgal Formation. Between Deniliquin and Echuca, for example, the present course of the main channel of the Murray River has been diverted to the south, by uplift of basement on the western side of the Cadell Fault. The result has been a ponding of drainage to form the Barmah Swamp forest (see Fig. 16). Pels (1966) examined stream traces at the surface and identified a channel (Green Gully), which formerly flowed across the block and is now tectonically stranded well above the general level of the floodplain. He suggested that the Murray River initially flowed around the northern margins of the up-faulted block, while the 'ancestral' Goulburn River flowed to the south. The Murray River subsequently switched to its present course to the south, although major distributary channels, such as the Edwards River, Bullatale Creek and Native Dog Creek, continued to flow to the northwest. Bowler (1967) obtained radiocarbon dates from former channels which suggested that this latest phase of movement on the fault occurred some 20 000 yrs. B.P. A detailed chronology of the fluvial history of this region is documentes in Bowler & Harford (1966a,b) and Bowler (1978a).

The catchments of the Lachlan, Murrumbidgee and Murray River systems, as well as other Victorian tributary rivers of the Murray, include much of southeastern Australia, north and west of the Dividing Range. The climatic regime within the Murray Basin is a semi-arid one, but the headwaters of many of the river systems draining into the basin receive higher rainfall. In the south, much of this higher rainfall occurs in the winter months and flooding in the southeast sometimes accompanies spring meltwaters. Flooding of the Darling River characteristically follows summer rains in southeastern Queensland. These periods of flooding are largely responsible for deposition of the Coonambidgal and other Upper Quaternary alluvial sediments. Butler (1958) and Pels (1966) suggested that the major rivers of the basin are eroding older sediments and are not depositing sediment carried into the basin. The river systems of the basin have clearly eroded within the older units, but within their confined floodplains the modern rivers are locally depositing lateral accretion sets, as evidenced by migrating scroll bars and stranded point bars. Little sediment reaches the terminus of

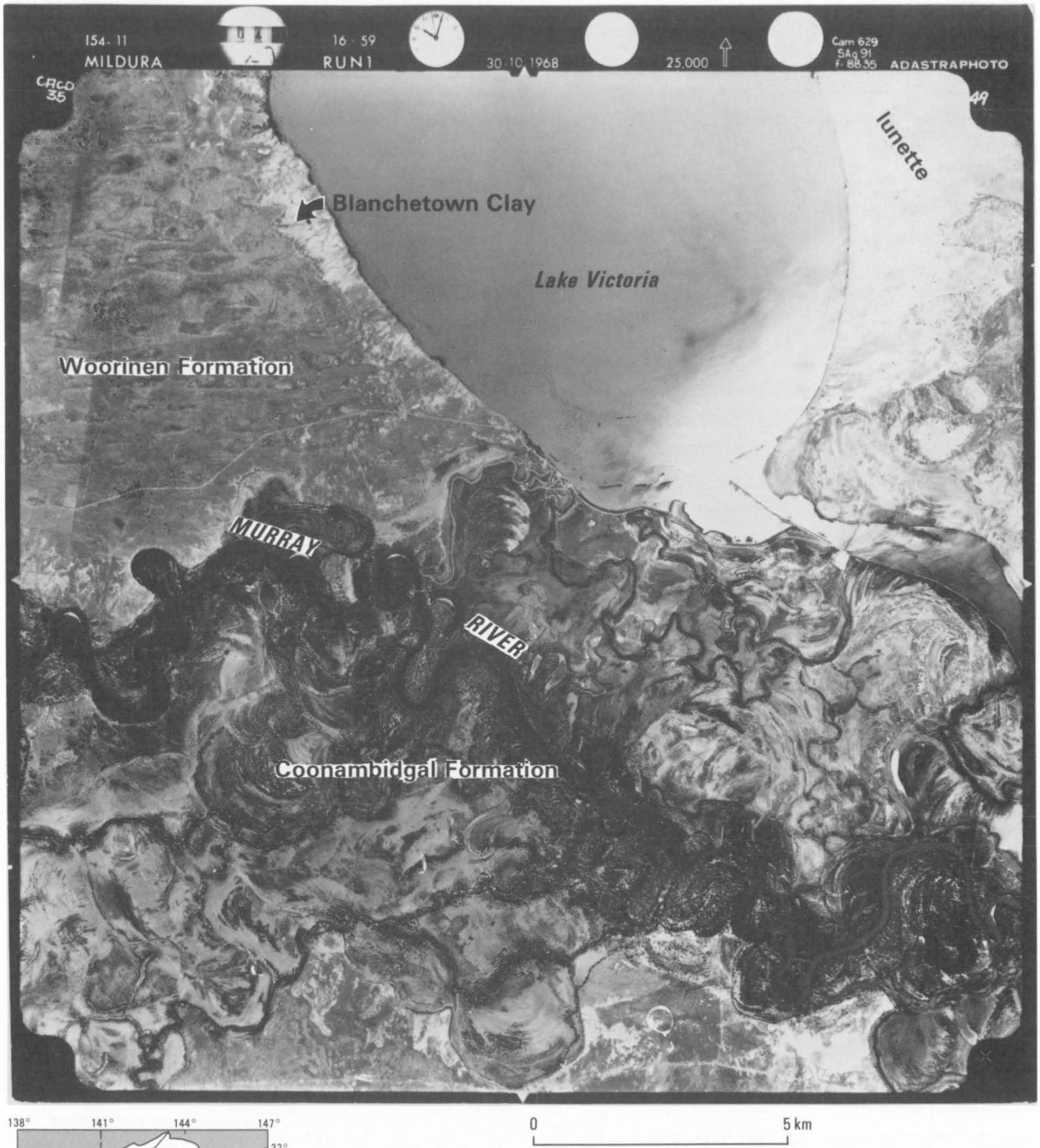


Fig. 158. Airphoto showing Quaternary floodplain of Murray River and southern Lake Victoria, entrenched within aeolian landforms of northwest MILDURA; photo from National Mapping RC9 Series, Mildura Run 1, No. 49; photographed 30/10/1968.

the Murray River at Lake Alexandrina.

The modern channels carry a suspended load and are characterised by low discharge, high sinuosity and low meander wave-lengths. The 'end-member' ancestral stream channels are morphologically similar in shape, but are much larger in size. As discussed by Schumm (1968a), the fluvial channels of the Riverine Plain are thought to have adjusted river length, channel width, depth, meander wavelength, sinuosity, and width-depth ratios in response to changes in climate and eustatic changes in sea-level/base-level. Schumm (1968a) examined the modern channel of the Murrumbidgee River near Darlington Point (meander wave-length 0.85 km) and

calculated a bank-full discharge of 280 m^3/sec., transporting a daily total of 2000 tons of sediment at a bank-full velocity of 90 cm/sec. An ancestral channel (meander wavelength 2.1 km) was calculated to have had a bank-full discharge of 1400 m^3/sec., transporting a daily total of 21 000 tons per day of sediment at a bank-full velocity of 1.3 m/sec. Schumm deduced that the ancestral channels carried a larger peak discharge and higher annual runoff than the modern channels, and thought that this could best be explained by a climate that was more humid than that of the present. Alternatively, as discussed by Bowler (1978a), the apparently high discharge can be explained without having to invoke a more humid climate if the ancestral streams were active during glacial ages, when seasonal periods of high discharge may have been related to annual spring-summer thaws and flooding of greater magnitude than that of today (i.e. an origin similar to that of 'prior' stream channels of 'Shepparton Formation').

Schumm (1968a) suggested that the transition from arid-phase 'prior' to more humid-phase 'ancestral' stream channel types accompanied an increase in discharge and a decrease in sediment supply, resulting in a decrease in channel gradient and an increase in channel length by formation of high sinuosity, low meander wave-length channels. He suggested that a subsequent decrease in runoff, but with no alteration to sediment input, resulted in the transition from ancestral to modern channels of similar shape, but greatly diminished size. Pels (1964a,b, 1966, 1971), however, recognised at least three phases of ancestral channel development, and suggested that incision occurred during increasingly pluvial periods and deposition during increasingly arid periods. As noted above, Bowler (1978a) also recognised at least three phases of modern and ancestral channel development associated with the Goulburn River. He observed, however, that the two older channel complexes carried a sandy bed-load rather than a suspended-load. He correlated deposition of the bed-load dominated Green Gully/Tallygaroopna (see 'Shepparton Formation') and Kotupna channels with the onset and culmination of arid glacial and periglacial conditions, and related the bed-load dominance to a lack of tree cover in both the basin and the adjacent highlands – resulting in high seasonal runoff and high input of coarse to medium-grained sand to the basin during spring thaws. The local presence of red clays of presumed aeolian origin is thought to indicate periods of seasonal aridity. The switch, from high discharge with bed-load dominance to low discharge with suspended load dominance (Goulburn Complex), can be related to diminished seasonal runoff and diminished sediment input, due to an increased vegetation cover accompanying the waning of glacial/periglacial influences.

Stratigraphic nomenclature and type section. The Coonambidgal Formation of Lawrence (1966) was modified from the 'Coonambidgal' of Butler (1958), who derived the name from Coonambidgal Creek on DENILIQUIN. Butler (1958), followed by Lawrence (1966), nominated the banks of Coonambidgal Creek near the northeast corner of Lot 75 in the Parish of Deniliquin as the type section.

Synonyms. In South Australia, Firman (1973) noted the possible equivalence of the 'Tartangan beds' of Hale & Tindale (1930) and Tindale (1957) to the Coonambidgal Formation, although P.A. Rogers (S.A.D.M.E., pers. comm., 1989) has subsequently suggested that the Tartangan beds are equivalent to the Bunyip Sand.

Stratigraphic relationships. In tributary highland valleys, Qa deposits unconformably overlie a range of Palaeozoic basement rocks and Tertiary sediments and volcanics. In the Riverine Plain, the Coonambidgal Formation is incised within the Shepparton Formation. Farther west, the unit is entrenched within Quaternary aeolian landforms of the Mallee region (Qdw, Qdp, Qdu), as well as equivalents of the Shepparton Formation and the Blanchetown Clay. Downstream, within the Murray River Gorge, Qa is progressively incised within older Tertiary formations (Tps, Tpb, Tml). The deposition of many source-bordering dune (Qad, Qdb) and lacustrine (Ql) deposits is intimately related to the distribution of Qa sediments. At the basin margins, and within some highland valleys, the Coonambidgal Formation and other late Quaternary alluvial sediments grade laterally into alluvial benches and colluvial aprons of piedmont polymictic fanglomerates (Pooraka Formation, Tawonga Gravel and other Qfr deposits).

In South Australia, the Coonambidgal Formation includes only the upper valley-fill of fine-grained silts and clays that occur in the modern valley of the Murray River, and underlying coarse sandy sediments are differentiated as the Monoman Formation (Table 39; Firman, 1973; Rogers, 1988, in press,b).

It should be noted that the Coonambidgal of Butler (1958) and the Coonambidgal Formation of Lawrence (1966) are equivalent to the Coonambidgal II and III of Pels (1971), but does not include the Coonambidgal I of Pels, which is covered by a yellow-red soil profile with carbonate segregations, and

is therefore currently correlated with the Shepparton Formation.

Aquifer characteristics. Sediments of the Coonambidgal Formation occur within the modern and ancestral drainage channels of the Murray Basin, where point-bar sands in bed-load dominated channels, such as those of the Kotupna Complex of Bowler (1978a), form local aquifers. The dominance of fine-grained sediments, however, and the proximity to readily available river water mean that the unit is only locally considered to be an aquifer. At the basin margins, and in eastern areas, drainage channels are currently major sites of recharge to the groundwater system. In places, they are sites of saline groundwater discharge.

Data sources. Stratigraphic and sedimentological descriptions of fluvial channels assigned to the Coonambidgal Formation are given by Butler (1958), Lawrence (1966, 1975, 1976a, 1988a), Schumm (1968a), Bowler (1978a), and O'Brien & others (1988). Geomorphic descriptions of the unit, including descriptions of the ancestral streams and interpretations of their origins are in Butler (1958, 1960), Pels (1964a,b, 1966, 1969a,b, 1970, 1971), Bowler (1966a,b, 1967, 1978a), Bowler & Harford (1966a,b), Langford-Smith (1966), Schumm (1968a), Butler & others (1973), and Bowler & Wasson (1984).

Unit: Semaphore Sand
Age: Holocene
Map symbol: Qhe

Lithology. The Semaphore Sand is dominantly an unconsolidated, locally mobile, white to pale-grey, calcareous, quartz sand. The quartz content varies, and carbonate, in the form of calcite and aragonite, occurs as grains, fossil detritus, or calcareous rhizoliths. Minor humic material is also present.

Distribution and thickness. The unit occurs adjacent to the Southern Ocean, and forms the modern beach and dune complexes (Fig. 128); its thickness is commonly of the order of 5 m, but is highly variable, up to a maximum in excess of 30 m. The Semaphore Sand extends south from the Murray Basin into the western Otway Basin.

Topography and vegetation. The Semaphore Sand forms a prominent ridge of dunes, the Younghusband Peninsula, between the Southern Ocean and the Coorong Lagoon (Figs 17, 128), and also includes beach dunes south of the Coorong, and north of the Murray River mouth. These beach dunes are locally mobile, and are vegetated by hardy grasses and small shrubs. The modern active beaches adjacent to the Southern Ocean are also included within the Semaphore Sand.

Stratigraphic relationships. The unit overlies deposits of the Pleistocene Bridgewater Formation (Firman, 1973), and grades laterally into the modern carbonate deposits of the Coorong. Near Lakes Alexandrina and Albert, Semaphore Sand also interfingers with muddy estuarine deposits of the St. Kilda Formation.

Palaeontology and age evidence. The Semaphore Sand contains abundant modern foraminifera throughout. Remains of medium to large marine organisms are mainly restricted to beaches and storm-surge deposits. Aboriginal middens have been found within the unit, overlain in places by recently deposited sand from mobile modern dunes (Firman, 1973, his fig. 27). Shells of the species *Turbo undulatus* dominated one such midden (in the Otway Basin), and at least two distinct Aboriginal cultures have been recognised from tools below, and shell middens within, the Semaphore Sand (Tindale, 1957; Firman, 1973): tools of the 'Tartangan' culture underlie the sand, and middens of the 'Murundian' culture occur within it. This implies that, at least in some areas, deposition of Semaphore Sand postdated the arrival of Aboriginal man in Australia, which is currently thought to have occurred about 45 000 – 40 000 yrs. ago. Thus, whilst the age of the basal Semaphore Sand is uncertain, it is unlikely to be older than latest Pleistocene, and may have started forming towards the end of the post-glacial rise in sea level (18 000 – 6000 yrs. ago).

Characteristics. The Semaphore Sand is characterised by its geographic position, its age, and its physiographic expression in the form of beach and coastal dune complexes. It is distinguished from the similar Bridgewater Formation on the first two of these characteristics, and from the partly contemporaneous St. Kilda Formation, and lagoonal sediments of the Coorong, on the basis of lithology.

Environment of deposition. The unit was deposited in a range of environments, including sub-tidal marine, littoral, and supra-tidal storm-surge zones, and back-beach aeolian dunes. On the leeward (eastern) side of the Younghusband Peninsula, blowout deposits from the dunes encroach into lagoonal sediments of the Coorong.

Stratigraphic nomenclature and correlations. The coastal beach and dune deposits of the Younghusband Peninsula were mapped by Thomson & Horowitz (1962) and Rochow (1969) on BARKER and NARACOORTE, respectively, but were not

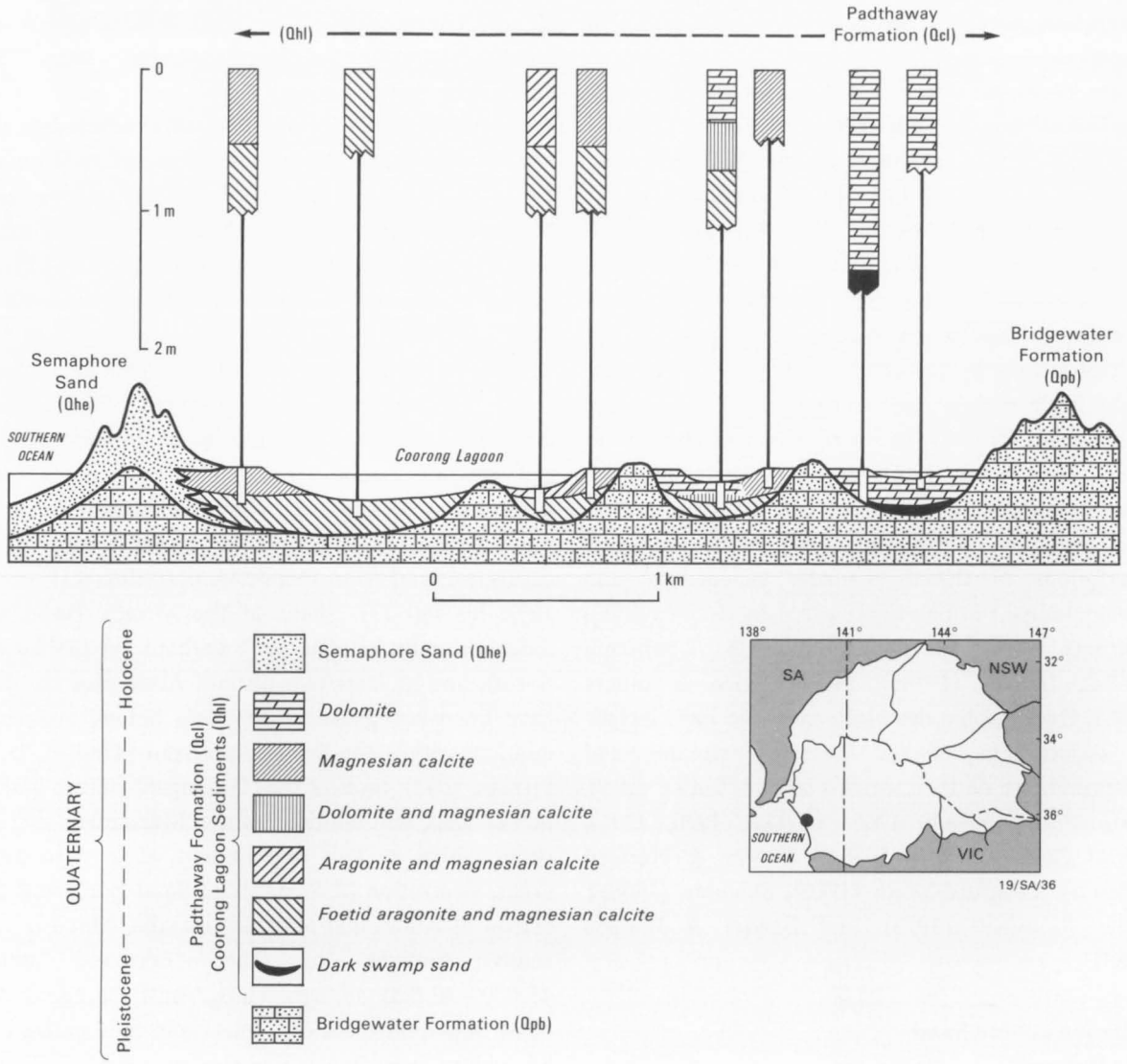


Fig. 159. Generalised cross-section through the Coorong and marginal-marine carbonate lakes (after Von der Borch, 1965; Firman, 1973).

named. The Semaphore Sand has never been formally defined, and hence lacks a type section. The name was used by Thomson (1969a) to describe the modern beach deposits of Gulf St. Vincent, and was applied to the coastal beach complexes of the Murray Basin and western Otway Basin by Firman (1973). The name appears to have been in local usage for some time, and refers to all the modern beach and coastal dune deposits of southeastern South Australia.

Hydrogeology and economic geology. The Semaphore Sand is highly porous and permeable, but is not of hydrologic importance. The unit has no economic significance, although occasionally deposits of Semaphore Sand block the mouth of the Murray River, raising the water level in Lakes Alexandrina and Albert, and resulting in flooding of low-lying land.

Remarks. The Semaphore Sand is the modern equivalent of the Pleistocene Bridgewater Formation, and provides a direct analogue for the environment of deposition of the older unit.

Data sources. The unit is described in Tindale (1957), Thomson & Horowitz (1962), Rochow (1969), Thomson (1969a), Firman (1973), and Thom (1983).

Unit: Unnamed Holocene lagoonal carbonate deposits
Age: Holocene
Map symbol: Qhl

Lithology. The world-renowned dolomitic carbonate deposits of the Coorong were described in detail by Von der Borch (1965, 1976). Sediments range from unconsolidated carbonate and sulphide-bearing mud

in open lagoons, to protodolomite and well-cemented dolomite in more restricted environments (Von der Borch, 1976; Fig. 159). A clastic component (quartz sand, with shelly and other carbonate detritus) is an important part of the sediment in the open lagoons.

The dolomite is predominantly of the microcrystalline variety, massive in nature, but with grain sizes of less than 10–20 microns (Von der Borch, 1976). It locally contains many of the structural elements characteristic of shallow-water to sub-aerial origin, including desiccation cracks, teepee structures, intraclast breccias, and birds-eye fenestrae. Carbonate minerals present include aragonite, magnesium calcite, calcite, protodolomite, dolomite, and magnesite. Local environment determines the combinations and relative proportions of these minerals in any one location.

Distribution and thickness. The dolomitic sediment of the Coorong is confined to that restricted-circulation lagoonal complex, and to its isolated southern extensions, as shown on the enclosed 1:1 000 000 map (Thomson & Horowitz, 1962; Rochow, 1969; Rogers, 1980a; Brown & Stephenson, 1985). The thickness of the sediment is variable, with a maximum of 6 m (Rogers, 1980a), but 1–2 m is more typical.

Stratigraphic relationships. The Coorong lagoonal sediments directly overlie the youngest parts of the Pleistocene Bridgewater Formation (Fig. 159); and is analogous to, but not directly related to, parts of the Pleistocene inter-ridge deposits of the Padthaway Formation. Modern aeolian processes have caused some interfingering between the Semaphore Sand and the Coorong sediment (Firman, 1973).

Palaeontology. Biotic remains within the Coorong sediment reflect the fact that the lagoon is inhabited by a modern restricted-marine fauna, decreasing in diversity towards the more extreme environments in the south. Gastropods, bivalves, foraminifera, ostracods, fish, and algae are common in the northern lagoon; bivalves are absent in the ephemeral conditions of the southern lagoon, and other forms are more poorly represented than to the north (Brown, 1965; Von der Borch, 1976). The animal and plant remains are locally incorporated into the carbonate sediment of the lagoon.

Age evidence. The Coorong lagoon has existed only since the end of the last glacial maximum (some 10 000 yrs. ago), and was formed by Holocene inundation of the eroded remnants of an indurated Pleistocene beach barrier system (Von der Borch, 1976). Late Holocene sea-level has been shown by radiocarbon studies to have stabilised relative to the Coorong area at around 6500 yrs. ago, in a manner analogous to other coastal areas of Australia (Thom & Chappell, 1965; Von der Borch, 1976), and presumably all the modern carbonate sediment is younger than that age. Chemical and clastic deposition of Coorong sediment is actively continuing today.

Characteristics. The Coorong lagoonal sediment is characterised by its geographic location and lithology. Although similar in some respects to the genetically similar sediment of the Padthaway Formation, the Coorong deposits are restricted to the most recent back-barrier lagoon, and usually have a higher carbonate content than that of the older infilled lagoons.

Environment of deposition. The Coorong is a restricted-marine lagoonal complex, separated from the Southern Ocean by a modern beach barrier bar, the Younghusband Peninsula. It has only one inlet, in the north, so that conditions become progressively more restricted towards the south. Von der Borch (1976) divided the Coorong into four environments: (1) permanent lagoon, (2) ephemeral lagoon, (3) proximal ephemeral lakes, and (4) distal ephemeral lakes. A vertical gradation from (1) through (4) is seen in many cores, as the Coorong is being gradually infilled from southeast to northwest.

Different mineral assemblages are found in the four environments. The lagoonal environment is by far the most widespread today, and can be divided into two sub-environments – North and South Lagoons. The North Lagoon is estuarine in character, with salinity fluctuating widely between approximately that of normal seawater and considerably lower values. Its salinity is controlled largely by seawater exchange through the single marine passage, combined with freshwater inflow from Lake Alexandrina, Lake Albert, and the Murray River. South Lagoon has no direct link to the Southern Ocean, from which it is separated by a 1.5 km wide and 30 m high barrier. It has no separate river input, although some percolation of saline water through the beach–barrier is possible. South Lagoon is connected to North Lagoon through the restricted Hells Gates channel, and its water reaches twice the salinity of normal seawater. Studies by Von der Borch (1965, 1976) show that the depositional environment of the Coorong has become increasingly more restricted in area since commencement of its formation.

Correlations. The Coorong lagoonal carbonate is similar in age and lithology to the sediment of the coastal lakes on PENOLA, which are also mostly cut

off from the Southern Ocean; both units are included in Qhl on the enclosed 1:1 000 000 scale geological map. The Coorong sediments are time equivalent to the modern beach barrier sands of the Younghusband Peninsula, the Semaphore Sand, with which they partly interfinger (fig. 26 of Firman, 1973).

Remarks. The Coorong and its sediment provide a modern analogue for the Pleistocene inter-ridge lagoonal sediment of the Padthaway Formation, and it would appear that there has been a succession of ridges and inter-ridge lagoons since 0.7 Ma., while the coast of the Gambier Sunklands prograded westwards (Cook & others, 1977). The Younghusband Peninsula and Coorong are merely the latest ridge and lagoon in the succession, and in fact overlie an older, Pleistocene barrier–lagoon complex (Von der Borch, 1976).

Data sources. The unit is described in Thomson & Horowitz (1962), Brown (1965), Thom & Chappell (1965), Von der Borch (1965, 1976), Rochow (1969), Firman (1973), Cook & others (1977), Rogers (1980a), and Burne & Ferguson (1983).

Unit: St. Kilda Formation
Age: Holocene
Map symbol: Qho

Lithology. The St. Kilda Formation consists of unconsolidated lacustrine mud, silt, sand, and organic detritus (both calcareous and carbonaceous). In times of high water levels in the estuary of the Murray River, the shallowness of the water table leads to local surface discharge of groundwater, which evaporates to form ephemeral salt crusts, particularly of halite and gypsum.

On the enclosed 1:1 000 000 geological map, areas adjacent to the coastal lakes of the Gambier Embayment have been included within St. Kilda Formation (see discussion below). In these areas, a lacustrine dolomite locally occurs, in addition to mud and silt. Von der Borch & Altmann (1979) have described in detail the estuarine, lagoonal, and lacustrine deposits of the Cooke Plains Embayment (on PINNAROO), which is a tongue of the St. Kilda Formation.

Distribution and thickness. The main occurrence of the St. Kilda Formation is adjacent to the modern estuary of the Murray River, in the swampy lowlands associated with Lake Alexandrina and Lake Albert (Fig. 17); in this area it has a maximum thickness of some 3 m. The areas around the southern coastal lakes, which are distinct from St. Kilda Formation *sensu stricto*, also have a thickness of up to a few metres.

Topography and vegetation. The unit forms low-lying plains, swamps, clay pans, and salinas, associated with the lakes of the Murray River estuary. The vegetation in this area consists of low grasses and swamp reeds; trees and shrubs are entirely absent in most places, as the water table is very close to the surface, causing water logging of any deep root systems. Equivalents of the St. Kilda Formation form small, low, flat, and almost unvegetated plains adjacent to the southern coastal lakes.

Palaeontology and age evidence. The St. Kilda Formation contains shell banks of Holocene organisms, although these and other deposits have not yet been accurately carbon dated. The St. Kilda Formation's sedimentology, geographic location, and stratigraphic position have been used by Rogers (1980b) to interpret it as forming during a time when the lakes of the Murray estuary covered a greater area. The most likely time for this was during the 'Flandrian' transgression, which took place some 6000 yrs. ago. The hydrologic backwater effect upon the Murray estuary would have caused a rise in the levels of Lakes Alexandrina and Albert. This hypothesis is supported by the fact that a rise in sea-level of 2–3 m today would inundate the entire area around the Murray estuary covered by St. Kilda Formation. Rogers (1980a) also related the expansion of the Murray River estuary to a period of increased rainfall between 8000–5000 yrs. ago. The ages of the St. Kilda Formation equivalents adjacent to the southern coastal lakes are less certain; these may have been deposited over several thousand years between the end of the latest glacial sea-level minimum and the present.

Characteristics and environment of deposition. The unit is characterised by geographic position, lithology, and to some degree by topographic expression. St. Kilda Formation is also characterised by its environment of deposition: it consists of lacustrine deposits of an enlarged Murray River estuary. The clastic (or non-salt crust) sediment of the St. Kilda Formation is lithologically identical to unconsolidated material currently being deposited in Lakes Alexandrina and Albert. The salt pans that locally form on the mudflats can also be regarded as a characteristic of this morphostratigraphic unit.

Stratigraphic nomenclature, type section, and correlations. The St. Kilda Formation is named after the coastal settlement of St. Kilda, north of Adelaide, in the St. Vincent Basin. The estuarine clay and shell banks of the Murray River, and the deposits adjacent to the southern coastal lakes, were equated by Fir-

man (1966a,f, 1973) with the deposits of Gulf St. Vincent, and given the same name.

The St. Kilda Formation, at least within the Murray Basin, is a morphostratigraphic entity rather than a geological unit in the strict sense. No subsurface type section has been formalized, but Firman (1973) regarded the sections from Robe Harbour Bores 8 and 10 (described by Sprigg, 1952a) as being typical of its lithology (see 'Remarks'). These sections are associated with a restricted lacustrine environment, and although they may be typical of St. Kilda Formation equivalents adjacent to the southern coastal lakes, are not necessarily typical of the major part of St. Kilda Formation, which is associated with an expanded Murray River estuary.

Stratigraphic relationships. The unit is a Holocene surficial morphostratigraphic unit, disconformably overlying unnamed Pleistocene lagoonal dolomites (Qpu), and unconformably overlying littoral to beach-ridge sands of the Pleistocene Bridgewater Formation (Qpb). The formation grades into and interfingers with other Holocene coastal units: the Semaphore Sand modern beach and dune complex (Qhe), lagoonal sediments of the Coorong (Qhl), modern alluvium (Qa), and deposits of coastal lakes (Qhl), and the lakes of the present Murray estuary.

Hydrogeology and economic geology. The St. Kilda Formation is largely saturated with near-surface groundwater, which locally crops out to form salinas. The shallowness of the water table makes the land unsuitable for most forms of agriculture, and dairy farming is the only significant land use.

Remarks. Von der Borch (1965) described a low, well-defined beach ridge associated with the Coorong, some 1.5 m above the current high-water mark for that lagoon. Firman (1973) assigned these sediments to the St. Kilda Formation on the basis of similar lithology and regional stratigraphic position. This usage was retained by Brown & Stephenson (1985), but an argument could be made for considering these sediments as precursors of the modern Coorong mud and carbonate (Qhl). Similarly, the lakes of the southern coast contain time-equivalent sediment associated with the 'Flandrian' transgression, but could be regarded as separate geological entities from the rest of the St. Kilda Formation.

Data sources. The St. Kilda Formation is described in publications by Sprigg (1952a), De Mooy (1959), Von der Borch (1965), Firman (1966f, 1973), Von der Borch & Altmann (1979), Rogers (1980a, 1980b), and Cann & Gostin (1985).

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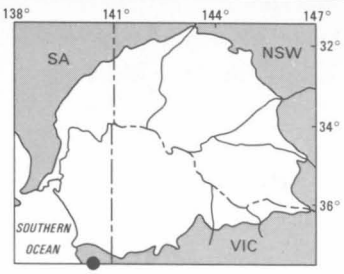

Fig. 160. Upper Cainozoic volcanic crater lake at Mount Gambier (PENOLA), in Gambier Embayment of Otway Basin to south of Murray Basin.

CAINOZOIC STRATIGRAPHY
UNDIFFERENTIATED SEDIMENTS AND VOLCANICS

Undifferentiated Tertiary sediments

Unit: Unnamed
Age: Undifferentiated Tertiary
Map symbol: Ta

Lithology. Tertiary deposits of moderately to poorly sorted, rounded to brecciated, pebble to boulder conglomerate, and granular to fine sand, are locally preserved within the highland areas bordering the Murray Basin. These lithologies are often set in a red-brown ferruginised and/or silicified matrix. Similar, but not necessarily ferruginised and silicified, weakly consolidated deposits also occur at lower levels within the highland valleys. The conglomerate and sand commonly have a sandy clay or kaolinitic matrix, and contain lenses of silt or clay. Relatively pure kaolin occurs at some localities (e.g. kaolin pits at Axedale, near Bendigo). The cobble and granular conglomerates consist mainly of rounded quartzite pebbles, but locally include lithic clasts from nearby basement rocks. For example, porphyritic mafic clasts occur in the Paleocene to Eocene 'Mangalore Gravels' in the southern Goulburn Valley (M.A. Reid, Rural Water Commission of Victoria, pers. comm., 1989).

Distribution and thickness. Small, isolated, poorly dated, undifferentiated coarse sediment of probable Tertiary age occurs as high-level residual ferruginised and/or silicified deposits capping older Precambrian to Palaeozoic basement rocks flanking the Murray Basin. Erosional remnants of many such deposits are exposed on higher valley slopes, and in stranded in-

terfluvial regions between highland valleys. They are generally only a few tens of metres thick, but in northern Victoria a number of valley-fill deposits are up to 100 m thick (Kenley, 1976c, 1988c).

Palaeontology and age evidence. The coarse-grained and/or deeply weathered nature of the sediment precludes preservation of diagnostic fossil material. Locally, however, the unit has fossil leaves, twigs, fruit and wood debris (Hunter, 1909; Singleton, 1935, 1941). Ferruginised sand and conglomerate of probable Renmark Group equivalents, near Benalla, preserve a 'Cinnamomum Flora' (Tickell, 1977b). Many intercalated basalt flows have been isotopically dated (Wellman, 1974), and these results indicate that some deposits are of Eocene age, whereas others are Pliocene–Pleistocene.

Interpretation of environment of deposition. The sediment was deposited in a range of environments including colluvial, valley-fill and high-level alluvial. Some sediment occurs within gullies and valley floors, but older deposits form stranded 'deep-lead' deposits of ancient drainage systems. Many deposits consist of quartz-rich residual weathering products cemented by ferricretes. The kaolin-rich deposits also represent the products of deep weathering. Auriferous sediment equivalent to the Calivil Formation, for example, was probably concentrated during deep weathering associated with the Mologa Surface of Macumber (1978a). Some kaolin deposits are thought to have been deposited in areas ponded by basalt flows.

Stratigraphic relationships. The sediments unconformably overlie a range of basement rock types. In the highland valleys, these include Cambrian to Silurian metasediment and Devonian granitoid, whereas in the Darling Basin they overlie well-cemented quartzite conglomerate and quartzose sandstone of Devonian age. In the northwest, they overlie, and are derived from, quartz-rich metasedimentary and other basement rocks of the Broken Hill and Willyama Blocks. In the highland valleys of northern Victoria, parts of the unit are probably contiguous with coarse clastics of the Calivil Formation, whereas others are older and equivalent to the Renmark Group. In the Stawell area, auriferous deep leads of 'Ta' are overlain by marine Mid-Tertiary sedimentary rocks (Brough Smyth, 1874; Taylor, 1876; Walcott, 1920). Elsewhere in the Victorian highlands, the 'Ta' sediment is intercalated with lava flows of 'Tv' or 'TQv' (Baragwanath, 1923). Some of the Victorian highland deposits are probably also equivalent to the Cowra and Lachlan Formations of Williamson (1964, 1969), which have been defined in the tributary valleys of the Lachlan Fold Belt to the east of the Murray Basin.

Economic geology. In places, the coarse sediment forms part of the deep lead systems, and in the south and east are locally auriferous and stanniferous (Hunter, 1909; Whiting & Bowen, 1976, 1988).

Data sources. Many of the highland deposits were first described during the periods of gold exploration in the late 19th and early 20th centuries (Brough Smyth, 1874; Taylor, 1876; Gregory, 1903; Wilkinson, 1907; Hunter, 1909; Baragwanath, 1923). The distribution of the major known deposits is shown on 1:250 000 scale geological maps published by the State Geological Surveys. Summary descriptions of the unit in Victoria are provided by Kenley (1976c, 1988c) and Whiting & Bowen, (1976, 1988).

Cainozoic volcanics

Small outcrops of Upper Tertiary to Quaternary volcanics occur throughout the highlands to the south and east of the Murray Basin. An extensive area of these 'Younger Volcanics', with a distinctive suite of volcanic landforms, occurs on HAMILTON, south of the Murray Basin at the southern margin of the accompanying 1:1 000 000 geological map. In addition, Holocene volcanics occur in the Mount Gambier region on adjacent PENOLA. Older Tertiary volcanics are less extensive, but remnants are exposed in the adjacent highlands on WANGARATTA and LAKE CARGELLIGO. These occurrences on the enclosed 1:1 000 000 map are briefly described in the following section, but a detailed decription is beyond the scope of this Bulletin. A comprehensicve volume describing the Tertiary volcanics, their geological setting, physical volcanology, petrology and geochemistry, has recently been compiled by Johnson (1989)

Unit: 'Older Volcanics'
Age: Early to Mid-Cainozoic (mainly Paleocene to Early Miocene)
Map symbol: Tv

Lithology. The 'Older Volcanics' consist mainly of black basaltic lava, agglomerate, and tuff. Many lava flows are associated with basalt or dolerite plugs and dykes, and some exposures consist entirely of basaltic plugs or dykes. The lava flows and plugs range in composition from silica-undersaturated basalt to phonolite (Ellis & Ferguson, 1976; Day, 1983; Price & others, 1988). Exposures on WANGARATTA have been described mainly as olivine basalt and

titanaugite basalt (Mines Department of Victoria, 1974b). Locally, the volcanics have inclusions of mafic and ultramafic rocks as well as underlying 'country rock'. Exposures of undifferentiated Tertiary volcanics on LAKE CARGELLIGO have been described mainly as bluish-black, fine-grained, porphyritic olivine leucitite (Pogson, 1967).

At many localities, the volcanics are spheroidally weathered to dark-red and are overlain by deep soil profiles. Veins of serpentinite and secondary zeolites have been noted at some outcrops. The volcanics are also associated with minor volcaniclastic and lava-ponded clastic sediments.

Distribution and thickness. The 'Older Volcanics' are confined to the highland areas flanking the southeastern and eastern Murray Basin, where they form small but widespread valley flows and remnant hill top cappings. In southern WANGARATTA, small outcrops in the Toomboollup area form remnants over a dissected peneplain (Laing & others, 1977). Farther north on WANGARATTA, volcanics are also preserved as stranded interfluves between tributaries of the King River (30 km south of Wangaratta). Further remnants of stranded flows occur 10 km southeast of Euroa. Some flows extend a short distance into the Murray Basin and have been intersected in bores such as Vic. D.M. Boorhaman No.1 in the Ovens Valley (Tickell & Humphrys, 1979), and Tertiary volcanics form an isolated hillock 5 km east-northeast of Pine Lodge towards the eastern margins of the Goulburn River floodplain.

Small areas of undifferentiated Tertiary volcanics also occur in areas flanking the eastern margin of the basin. The largest areas of outcrop are immediately west of the town of Lake Cargelligo (LAKE CARGELLIGO) and nearby areas to the southeast (Pogson, 1967).

The 'Older Volcanics' are also known to be present in the subsurface beneath the extensive area of outcrop of 'Younger Volcanics', although no outcrops are known. Boreholes drilled into the Mesozoic–Cainozoic sequence of the Otway Basin, at the southern margin of the accompanying 1:1 000 000 geological map have locally encountered single and multiple basaltic flows intercalated within Tertiary sediments, as well as dolerite dykes (Abele & others, 1976, 1988).

Outcrop and geomorphic expression. Erosional remnants of Tertiary volcanics are located in valley floors, on valley sides and on interfluvial ridge crests and spurs. Within the valleys, erosion of former valley-fill volcanics has resulted in development of steep-sided stranded interfluves. Erosion and weathering of formerly extensive Tertiary volcanics deposited over plateau areas, such as those in southern WANGARATTA, has resulted in small remnant outcrops.

Age evidence. Based mainly on geomorphic expression, Hills (1938) suggested that the 'Older Volcanics' were mainly Oligocene–Early Miocene, whilst Singleton & Joyce (1969) suggested that they were mainly Paleocene and Eocene. Subsequent isotopic age determinations indicate that the 'Older Volcanics' extend from Paleocene to Early Miocene (Bowen, 1974; Wellman, 1974; Wellman & McDougall, 1974; McKenzie & others, 1984). Outcrops in southern WANGARATTA provided radiometric ages of between 5.6 and 43 Ma (Wellman, 1974; Birch, 1976). A number of small basalt and dolerite dykes intruding Ordovician metasediments crop out in southern BENDIGO, and were originally thought to be Cainozoic in age (Stillwell, 1913). Isotopic dating by Wellman (1974) has revealed, however, that these particular exposures are Jurassic in age. Olivine leucitite exposures on CARGELLIGO gave isotopic age determinations of between 10.2 and 14.9 Ma (Wellman & others, 1971).

Jones & Veevers (1982) compiled a histogram of all available isotopic age determinations from throughout southeastern Australia and found that volcanic activity was nearly continuous throughout the Tertiary with the exception of periods of volcanic quiescence at the Paleocene–Eocene boundary, in the mid-Oligocene, and in the early-Late Miocene.

Interpretation of environment of deposition. Most of the volcanics are thought to have been emplaced during sub-aerial eruption onto a highland landscape of considerable relief, and mainly flowed down the then existing valleys. Jones and Veevers (1982), for example, noted that the basalts of Late Eocene age occur over an elevational range of 600 m within the present-day topography. In many instances, the flows therefore preserve the shape of fossil valleys. Jones & Veevers (1982) suggested that volcanism accompanied episodic uplift of the highlands, whereas periods of volcanic quiescence accompanied periods of tectonic settling of the highlands. They also noted that their histogram of isotopic age determinations partly reflects increased preservation potential with decreasing age.

Stratigraphic relationships. On WANGARATTA, the Tertiary volcanics unconformably overlie Ordovician metasedimentary rocks, Devonian granite, Devonian volcanics, and Carboniferous sedimentary rocks. Some flows are underlain by, or intercalated with, undifferentiated Tertiary alluvium (Ta).

Economic geology. Some gold placer deposits occur within 'deep leads', preserved beneath the volcanics.
Data sources. Descriptions of 'Older Volcanics' sites are recorded in Edwards (1938, 1939), Hills (1938, 1939), Pogson (1967), Singleton & Joyce (1969), Gunn (1974), Mines Department of Victoria (1974b), and Laing & others (1977). The petrography of the 'Older Volcanics' is summarised in Ellis & Ferguson (1976), Day (1983), and Price & others (1988). Isotopic age determination are given in Wellman & others (1971), Bowen (1974), Wellman (1974), Wellman & McDougall (1974), Birch (1976), Day (1983), McKenzie & others (1984), with additional sources listed in Jones & Veevers (1982), and Price & others (1988). Thie volcanics hace also been described in detail in a number of recent papers in Johnson (1989).

Unit: 'Newer Volcanics'
Age: Late Tertiary to Quaternary (mainly Pliocene to Recent; minor Late Miocene)
Map symbol: TQv

Lithology. The 'Newer Volcanics' consist of grey and black basaltic lava, black and red-brown agglomerate, scoria, tuff, as well as associated volcaniclastic sediments. The basalts comprise mainly nepheline basanite, but range from trachyte and trachybasalt through alkali olivine basalt to minor olivine tholeiite (Abele & others, 1976, 1988; Ellis & Ferguson, 1976; Price & others, 1988). In comparison with the 'Older Volcanics', dolerite dykes are relatively rare in the 'Newer Volcanics'. The pyroclastics include a wide range of ejecta ranging from coarse bombs and blocks to fine ash. Inclusions are rare in the lavas, but some of the bombs in the scoria cones have fragments of older basalt, mafic and ultramafic clasts, as well as rare xenoliths of the underlying and concealed sedimentary and granitic country rocks (Ellis & Ferguson, 1976; Irving & Green, 1976; Price & others, 1988). These include high-pressure lherzolite nodules thought to be mantle-derived.

In many areas, the volcanics are weathered to a deep brick-red to purple-red colour. The youngest lava flows (such as those around Mount Napier on HAMILTON at the southern margin of the enclosed 1:1 000 000 geological map) are relatively fresh in appearance and are overlain by a thin soil cover. In contrast, many of the older flows are characterised by deep weathering profiles of red-brown and black soils grading to laterites developed over zones of spheroidally weathered basalt (Boutakoff, 1963; Gibbons & Gill, 1964). In addition to deep weathering, many deposits have been sudject to hydrothermal alteration, and have veins of secondary zeolites.

The associated volcaniclastic sediments consist largely of reworked volcanolithics, but they also include intercalations of lacustrine clay, silt, carbonaceous clay, peat and diatomite.
Distribution and thickness. The 'Newer Volcanics' occur mainly in an extensive east–west oriented belt blanketing 15 000 km^2 of southern Victoria and extending into southeastern South Australia as far as Mount Muirhead. At the western end of the belt in South Australia, Sheard (1978) identified 17 small eruptive centres, all on PENOLA (Joyce, 1971; Sheard, 1983, 1985, 1986). The best known of these are at Mount Shank and Mount Gambier (Fig. 160), where a spectacular crater lake provides much of the town water supply (Waterhouse, 1977). In Victoria, the volcanics are particularly well developed on HAMILTON south of the Murray Basin.

Additional isolated outcrops of 'Newer Volcanics' also occur at a number of localities in northerly draining valleys of the Victorian highlands. Prominent flows are preserved in the trunk and tributary valleys of the Loddon and Campaspe Rivers (Hunter, 1909), at the southern margins of the Murray Basin on ST. ARNAUD (King, 1977) and BENDIGO (King & Wilkinson, 1975; Wilkinson, 1977). Cainozoic volcanic remnants display a characteristic pattern of magnetic anomalies over some areas of the Victorian highlands (see 'Aeromagnetics' and Figs 19, 160, and Plates 16, 17).
Outcrop and geomorphic expression. The volcanics of the Western District of Victoria form an undulating plain of complex lava fields, interrupted by numerous small sites of eruption forming low-angle lava cones, steep-sided scoria cones, maars, tuff-rings, and calderas as well as complex volcanoes (Ollier, 1964a,b, 1967a,b; Jenkin, 1976, 1988). No large volcanoes were formed and at least 300–400 sites of eruption have so far been identified (Ollier & Joyce, 1976; Joyce, 1988) Most cones are less than 100 m in height and extend over only a few square kilometres. A few eruptive centres, such as the volcanic remnant at Mount Napier, consist of a number of parasitic cones. Many slightly elevated areas of composite lava flows are locally referred to as 'stony rises'. These form broad plains with hummocks (volcanic tumuli) and depressions. Drainage patterns have been particularly disrupted by lava flows, and numerous lava-dammed lakes and ponded areas of low-lying swampy ground occur throughout the volcanic province. Crater lakes occur within unbreached cones, in maars, and in maar complexes.

The influence of resistant volcanics on drainage patterns is also evident in the highland valleys where lava flows have diverted rivers. In places, where rivers flow over resistant exposures of the basalt, small waterfalls occur at the outcrop margins. In most cases, erosion has resulted in undercutting of the lava flows and in development of steep-sided stranded interfluves (Hunter, 1909; Edwards, 1938; Ollier & Joyce, 1964). At some localities, all that remains of the original volcanic flow is a series of isolated small hilltops and spurs capped by basalt. The Campaspe River and its tributaries, for example, form lateral streams and currently flow along the margins of steep-sided resistant remnants of former valley-fill flows, which displaced the original rivers at the time of eruption. In the Campaspe Valley, this series of northerly trending lava flows defines the fossil valley of the pre-Pliocene Campaspe River. In the south, a lava flow appears to have ponded the depression which is now infilled by Lake Eppalock, and the present-day outlet creek forms a lateral stream adjacent to a major flow. The Coliban River was originally a tributary of the Campaspe, but its valley was blocked by a resistant lava flow, and the tributary re-directed to the north (Ollier, 1967b).

Internal geometry. In the Hamilton area, the scoria and ash deposits are bedded and generally dip outwards from the crater from which they were erupted, although some ash deposits have been asymmetrically distributed by the then prevailing wind (Ollier & Joyce, 1976; Joyce, 1988). In western Victoria, lava flows form laterally extensive sheets, which are individually only a few metres thick but are normally superimposed. These lava fields display a range of features including surfaces of ropy lava, pressure ridges, columnar jointing, lava blisters, lava canals and lava caves with lava stalactites, as well as steam bubbles and rare pillow lavas (Ollier, 1967b).

In the highlands, some residual cappings (e.g. Woodstock area; BENDIGO) of former lava plains are only some 20 m thick (Wilkinson, 1977), whereas the flows in the confined Loddon and Campaspe valleys are up to 100 m thick. These highland valley occurrences essentially reflect the morphology of the fossil valleys into which the lavas originally flowed.

Age evidence. Holocene components appear to be confined to the western end of the volcanic belt. In southeast South Australia, radiocarbon age determinations from charcoal in fossil soil horizons sealed beneath ash deposits at Mount Gambier have been dated at 4830 $\pm$ 70 yrs. B.P. (Ferguson & Rafter, 1957) and 1410 $\pm$ 90 yrs. B.P. (Blackburn, 1966b; Kigoshi & Kobayashi, 1966; Sheard, 1978). At Mount Shank, a radiocarbon date of 18 100 $\pm$ 350 yrs. B.P. was obtained by Polach & others (1978). Palaeomagnetic results from basalt and clastics from both the above volcanic centres indicate an age either greater than 7000 yrs. B.P. or between 5000 and 1000 yrs. B.P. (Barbetti & Sheard, 1981). Barton & McElhinny (1980) suggested that no volcanic events are younger than 5000–6000 yrs. B.P. In contrast, radiocarbon ages obtained by Blackburn & others (1982) from charcoal samples from beneath tuff horizons at Mount Gambier ranged from modern to 8000 yrs. B.P., but suggested that major volcanic events occurred between 4000 and 4300 yrs. B.P. In western Victoria, based on geomorphic evidence, most of the volcanics are considered to be of Pliocene to Pleistocene age. At Mount Napier and Mount Rouse on HAMILTON, for example, maars are particularly well preserved and some flows are largely unweathered suggesting a relatively recent age. In contrast, many older flows consist of spheroidally weathered basalt mantled by deep soils and laterite (Ollier, 1967b). McDougall & Gill (1975) obtained ages of between 0.3 to 0.4 Ma, whereas Ollier (1985) reported ages of 1.8 Ma. At Mount Napier, Gill & Elmore (1973) obtained a radiocarbon date of 7300 yrs. B.P. from charcoal underlying volcanics. Isotopic age determinations on basaltic samples obtained elsewhere in the lava fields and at other localities in the highlands of Victoria fall in an age range from 4.5 Ma to 0.6 Ma (McDougall & others 1966; Aziz–Ur–Rahman & McDougall, 1972; Wellman, 1974).

In the highland valleys, the 'Newer Volcanics' overlie Upper Miocene–Pliocene Calivil Formation, but pre-date fluvial sediments of the Coonambidgal Formation (Lawrence, 1975).

Characteristics. The 'Newer Volcanics' were originally differentiated from the 'Older Volcanics' on the basis of geomorphic expression and on the degree of preservation of original eruptive features. In addition, however, the 'Newer Volcanics' were predominantly erupted in western areas, and are not found farther east than the Strathbogie district (WANGARATTA; Laing & others, 1977), whereas the 'Older Volcanics' occur in eastern localities, but are relatively rare in the west. Dykes are more abundant in the 'Older Volcanics', possibly as a consequence of their relative degree of erosion. Some highland exposures are difficult to differentiate, but most outcrops of Cainozoic volcanics have now been isotopically dated.

Interpretation of environment of deposition. In the lava fields of western Victoria, large volumes of sub-

aerial basaltic lava and pyroclastics were extruded over a pre-existing plain. The volcanics were erupted mainly from the several hundred volcanic cones with central vents, but many of the lava flows may also have been extruded from fissures (Ollier & Joyce, 1976; Joyce, 1988). None of the eruptive centres developed into major volcanoes, and many of the maars were the result of single explosive events, which are thought to have been phreatic in origin.

The volcanic eruptions were accompanied by disruption to local drainage patterns with the consequent development of ponded lakes and local swamp deposits around the margins of many lava flows. Lacustrine sediments accumulated within these areas (Ollier, 1967b). Additional lacustrine sediments accumulated within crater lakes and maars.

In the Victorian highlands, remnants of the valley-fill volcanics are present at a number of different elevations, indicating that the lavas were extruded on to a relatively dissected landsurface (Ollier & Joyce, 1976; Joyce, 1988). Singleton & Joyce (1969) suggested that volcanism occurred over an area of domal uplift accompanying arching of the Victorian Highlands, but, as noted above, Jones & Veevers (1982) related volcanic activity in the highlands to periods of tectonic uplift, and periods of volcanic quiescence to periods of tectonic settling.

Volcanic activity took place throughout the Cainozoic, but in both the highlands and in western Victoria, volcanism is generally considered to be extinct (Ollier, 1967b; Hilmansyah, 1985). The relatively recent age determinations for some of the phreatic explosive events at the western end of the province (Sheard, 1978, 1986), as well as the presence of hot geothermal groundwater (Cull, 1978, 1979), indicate that the volcanic province retains some residual heat.

Stratigraphic nomenclature. The Upper Cainozoic volcanics of Victoria were collectively named the 'Newer Volcanics' in order to differentiate them from the Lower to Mid-Cainozoic 'Older Volcanics'. Individual volcanic features and remnants of valley-fill flows have been given a number of informal names, but no formal stratigraphic nomenclature has thus far been proposed to define the volcanic province and its component features.

Stratigraphic relationships. The extensive lava fields blanket a variety of Palaeozoic basement rocks, as well as Cretaceous and Cainozoic sedimentary rocks.

Aquifer characteristics. The hydraulic conductivity of the volcanics is highly variable (Lawrence, 1976e), but zones of high permeability with yields of up to 60 l/sec occur in the pyroclastics as well as in fractured, jointed, and vesicular lavas to the south of those shown on the enclosed 1:1 000 000 geological map, (Newton, 1954; Lawrence, 1969; Thompson, 1972, 1974). Salinities range from 50 to 8000 mg/l TDS, but are generally low in the younger lavas (Lawrence, 1976e).

Economic geology. In western Victoria, scoria and tuff have been extensively quarried for road construction, both as a base material and as bitumen aggregate (McKenzie, 1977). Scoria has also been used to line drainage channels, as a base for pipes, as railway ballast, and as garden ornamentation. A large scoria quarry at Mount Rouse supplies the City of Hamilton and further quarries are located at Mount Napier. In the highland area, lava from a large quarry east of Axedale provides basalt aggregate and screenings for the City of Bendigo (Wilkinson, 1977).

In the Loddon and Campaspe (Hunter, 1909) valleys of northern Victoria, lava flows of the Newer Volcanics form a resistant capping over Pliocene and older alluvial sediments and have locally resulted in the preservation of some 'deep lead' auriferous placer deposits (Whiting & Bowen, 1976, 1988).

Data sources. Descriptions of the geology of the 'Newer Volcanics' are recorded in the following references: Brown (1884), Howchin (1901), Hunter (1909), Fenner (1921), Edwards (1938), Skeats & James (1937), Hills (1938, 1939, 1959, 1975), Hutton & others (1959), Boutakoff (1963), Ollier (1964a,b, 1967a,b, 1985), Ollier & Brown (1964, 1965), Ollier & Joyce (1964, 1976), Gill & Gibbons (1969), Joyce (1971, 1975, 1984a,b, 1988), Gill (1972, 1978), Ellis & Ferguson (1976), Irving & Green (1976), Jenkin (1976, 1988), McKenzie (1977), Sheard (1978, 1983, 1985, 1986), Hilmansyah (1985), and Price & others (1988). The volcanics have recently been described in detail in Johnson (1989).

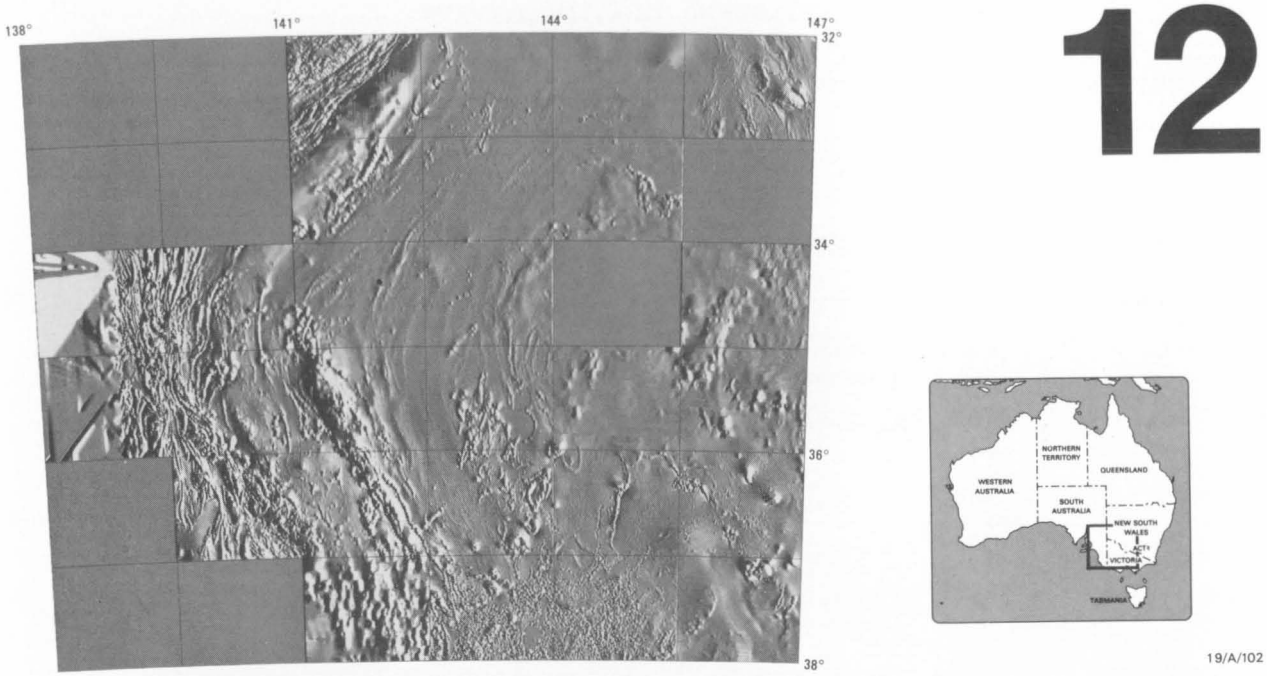

Fig. 161. Grey-scaled, east–west gradient total magnetic intensity imagery. For reference purposes imagery also shows 1:250 000 map sheets, which are indexed on Figure 163. Compiled mainly from original digital aeromagnetic data, but includes some digitised analogue data (e.g. HAMILTON). Suitable digital or analogue data were not available from some areas (e.g. HAY 1:250 000 Sheet area). Dimensions of area covered are 850 km east–west, and 665 km north–south. Data processing by V. Anfiloff and S. Dennis, BMR.

GEOPHYSICAL INVESTIGATIONS

Gravity

A number of regional and detailed gravity surveys were undertaken over parts of the Murray Basin during the course of petroleum exploration (Table 40). Gravity surveys were also undertaken during the investigation of Upper Permian coal deposits in the Oaklands Basin beneath the southeastern Riverine Plain (e.g. Thyer & Vale, 1952). These early surveys established the general configuration of basement structural features beneath the Murray Basin (Fig. 20), and many of the gravity-defined features have been confirmed by later seismic surveys. In particular, gravity was used to define many of the structural features in northwestern areas of the basin. For example, steep gravity gradients bordering the Menindee Trough suggest that the trough is faulted against the Broken Hill Block to the northwest, and the Scopes Range High to the north (Bauer & others, 1979). A Bouguer gravity saddle separates the Menindee Trough from the Tararra Trough to the southwest, which is in turn separated from the Renmark Trough by a similar saddle. The Blantyre Trough is less well defined and may be a composite of several structural lows. The presence of other gravity-defined troughs, such as the Ivanhoe Trough, has been confirmed by drilling, but in some areas the interpretation of gravity trends beneath the Murray Basin is complicated by the presence of granitoid bodies. Petroleum exploration wells, such as NSW Oil & Gas Hay No.1 (Haskell, 1970b) and Woodside Bundy No.1 (Shiels, 1962), were drilled into gravity lows, but encountered granitoids within a few hundred metres of the surface. As noted below (see 'Magnetotellurics' and 'Seismic'), Dampney (1977) and Vozoff & Cull (1981) have suggested that the steep gravity gradients of the Wentworth Gravity low, which define the 'Wentworth Trough', may also be complicated by the presence of shallow granitoid basement (e.g. as encountered by N.S.W Oil & Gas Nambucurra No.1; Haskell, 1970b). Similarly, the presence of a shallow basement ridge forming the Lake Wintlow gravity high has not been confirmed by drilling, and the gravity feature may be due to the presence of vol-

TABLE 40. GRAVITY SURVEYS

Survey	*Year*	*Area*	*Company*	*Reference*
Oaklands-Coorabin	1948/49	Oaklands Basin	Bureau of Mineral Resources	Thyer & Vale (1952)
Murray Basin	1957		Frome-Broken Hill Co. Pty Ltd	Frome-Broken Hill (1957a)
Wentworth-Pooncarie (Mount Darnick)	1957	Wentworth/Pooncarie/ Mount Darnick	Australian Oil & Gas Corp. Ltd	Australian Oil & Gas Corporation (1957a)
Western District	1957	Vic.	Bureau of Mineral Resources, Australia	Wiebenga (1957)
Oil Prospectin Permit 14	1958	Horsham area	Bureau of Mineral Resources, Australia	Neumann & Van Son (1958)
McKenzie River	1959	Vic.	Bureau of Mineral Resources, Australia	Neumann & Van Son (1959)
Oaklands	1960	Oaklands Basin	Australian Oil & Gas Corp. Ltd	Australian Oil & Gas (1960a)
Murray Basin	1960	Carrathool to Loxton	Bureau of Mineral Resources, Australia	Watson (1962)
Murray Plains	1960	Renmark-Pata-Wanbi	Hackathorn Oils Ltd	Hackathorn Oil (1961)
Deniboota	1962		Woodside (Murray River) Oil Co. Pty Ltd	Woodside Oil (1962)
Griffith	1962	Griffith area	Geological Survey of New South Wales	Pegum (1962)
East Darling	1963	Northern MANARA & IVANHOE	Wongela Geophysical Pty Ltd	Planet Exploration (1963)
Loxton, South Australia	1963	Renmark Trough	Beach Petroleum N.L.	Stackler & Yakunin (1962)
Northwest Murray Basin	1963	Northern Murray Basin in S.A.	South Australian Department of Mines & Energy	Kendall & Seedsman (1964)
Stephens Creek	1963/64	Barrier Highway	Geosurveys of Australia Pty Ltd	Sprigg (1963/64)
Menindee	1964	Menindee	Geophysical Service International	North Australian Petroleum (1964)
Murray Provinces	1964	South Australia	Australian Oil & Gas Corp. Ltd	Australian Oil & Gas (1965a)
Ivanhoe	1965	parts of BOOLIGAL, MANARA, POONCARIE & CARGELLIGO	Wongela Geophysical Pty Ltd	Texam Oil (1965)
Nulla Nulla	1965	N.W. Murray Basin, near Tararra Homestead	Australian Oil & Gas Corp. Ltd	Moorecroft (1965a)
OPL 36 survey	1965	S.A.	Blumer & Associates Pty Ltd	Blumer & Webb (1965)
Murray Province	1966	Renmark to S. of Loxton	Beach Petroleum N.L.	Stackler & Sprigg (1966)
Scopes Range	1967	Darling River near Meninde. SW to S.A. border	Geosurveys of Australia Pty Ltd	Alliance Oil (1967)
Four Corners	1968	Darling area near Menindee, S.W. to S.A. border	Geosurveys of Australia Pty Ltd	Alliance Oil (1968a)
Hamley	1968	N. of Renmark	Mines Administration Pty Ltd & Namco Geophysical Co.	Associated Australian Oilfields (1968)
Murrumbidgee	1968	Oaklands Basin	Planet Exploration Co. Pty Ltd	Planet Exploration (1968a) & Bluestone (1969)
Peri Lake	1968	Peri Lake	Planet Exploration Co. Pty Ltd	Planet Exploration (1968b)
Blantyre Basin	1969	100 km E.S.E. of Wilcannia	Planet Management & Research	New South Wales Oil & Gas (1969a)
Jerilderie Detailed Gravity Survey No.1	1969	800 sq.km N.E. of Jerilderie	Petty Geophysical Co.	Planet Exploration (1969a)
Goulburn & Ovens River Valleys	1972	Shepparton & Wangaratta areas	Bureau of Mineral Resources, Australia	Pettifer (1973) & Pettifer & others (1987)
Goulburn Valley	1973	Rochester to Cobram	Bureau of Mineral Resources, Australia	Pettifer & Kerec (1975) & Pettifer & others (1987)
Reconnaissance Gravity South-east Australia	1973/74	S.E. Australia	Bureau of Mineral Resources, Australia	Zadoroznyj (1975)
S.W. Murray Basin	1980	Traverses in Binnie, Notts Well, Cadell, Kiki Kiki, Sandy Peake, McDonald Downs, Ramco areas	Solo Geophysics Co.	CRA Exploration (1980)
Murray Basin	1987	West-central area	Bureau of Mineral Resources, Australia	Anfiloff (1987)
Avon-Richardson catchment	1989	Southern margin	Victorian Department of Industry, Technology & Resources	Withers (1989)

canics, which may not necessarily form a shallow basement ridge.

As part of a program aimed at complete coverage of the Australian continent, BMR undertook helicopter supported gravity surveys to infill areas of data deficiency (e.g. Zadoroznyj, 1975). As a result, the entire Murray Basin is now covered by a digitised gravity dataset from which regional gravity and Bouguer Anomaly maps can be generated at various scales (Fig. 7; Plate 15). The average spacing of BMR data points is about 11 km (Anfiloff & others, 1976). In the Murray Basin, however, these

have been supplemented by large numbers of observations from relatively detailed traverses, involving the generation of long profiles in key areas by BMR. These indicate that the gravity method provides a cheap and effective first-pass tool, which can be used to define the shape of the shallow basement concealed beneath the basin.

Wyatt & others (1980) reviewed geological sources of gravity anomaly fields in the Lachlan Fold Belt to the east of the Murray Basin, and noted a major discontinuity in gravity trends, roughly coincident with the eastern margin of the basin. Wellman (1976) used free-air anomalies over 1 square degree areas to determine variations in thickness of the Australian crust, and predicted crustal thicknesses of around 35 km beneath the Murray Basin, and at least 40 km beneath adjacent highlands to the south and east.

Data sources: Gravity surveys undertaken during the course of petroleum exploration are listed on Table 40. The enclosed 1:2 500 000 gravity map was generated from the BMR gravity databank maintained by the Geophysical Observatories and Mapping Branch. A 1:5 000 000 Bouguer gravity map of Australia was published by BMR in 1976 (Bureau of Mineral Resources, 1976). A description of the computerised gravity databank, as well as the procedures involved in the compilation and production of the Gravity Map of Australia is in Anfiloff & others (1976; see also Anfiloff, 1985). Contoured pre-1981 Bouguer Anomaly maps of most 1:250 000 Sheet areas were initially printed at a reduced 1:500 000 (Fig. 7). Almost the entire Murray Basin is now covered by computer generated maps in the form of regularly up-dated dyelines and transparencies – available at 1:250 000 from the Copy Service of the Bureau of Mineral Resources. Gravity surveys undertaken in northwestern areas of the basin during the course of exploration for hydrocarbons, up to the mid-1970's, have been described in Bauer & others (1979). The major reports used to construct the gravity databank in the Murray Basin region are by: Kendall & Seedsman (1964), Texam (1965), Alliance (1967), Planet Exploration (1968a), New South Wales Oil & Gas (1969a), and Zadoroznyj (1975). Figures showing regional Bouguer Gravity Anomaly contours and interpreted structural features are given in Bembrick (1974), Thornton (1976), Brown & others (1982), and Brown (1985). Gravity and aeromagnetics on HORSHAM, at the southern margin of the Murray Basin, have been interpreted by Willocks (1987).

Aeromagnetics

A number of regional aeromagnetic surveys were flown during the course of hydrocarbon exploration in the Murray Basin (Table 41). These indicated that the Murray Basin is underlain by an irregular magnetic basement, and confirmed the general structural configuration of underlying troughs and basement features, as defined by gravity. Depth to magnetic basement estimates were obtained from several of the troughs (summarised in Bauer & others, 1979). McIntyre & Wyatt (1978), for example, estimated a depth to magnetic basement of 7 km in the Menindee Trough. Unfortunately, however, many of the surveys were only partly successful in establishing depths to basement, owing to structural complexities and a lack of uniformity in the suspected basement rocks types. BMR subsequently undertook a number of aerial surveys as part of a program aimed at complete coverage of the Australian continent. Some of the early data are analogue, but most surveys generated digital total-magnetic intensity datasets. Surveys were flown at a continuous ground clearance of 150 m on east–west flight lines 1500–3200 m apart. Many of these data have now been published as 1:250 000 Series contoured maps (Fig. 7), while the digital datasets have recently been reprocessed for presentation in the form of magnetic imagery (Plates 16, 17).

Total-magnetic intensity gradient maps: Regional magnetic datasets from southeastern Australia have been available in stacked profile and contour form for some years (Tucker & Hone, 1984), but it is only recently that the availability of digital data presented in image form has allowed effective use of the data in the identification of concealed magnetic features. The BMR Geophysical Observatories and Mapping Branch has produced a number of large area grey-scaled and colour-scaled magnetic images of standard 1:1 000 000 Sheet areas (Tucker & others, 1985a). The images of the Murray Basin region (Plates 16, 17; illustrated at reduced scale in Figs 161, 162) are composites of four 1:1 000 000 maps – Tucker & others, 1985b). In areas lacking digital coverage, older analogue data have been converted to digital form, although in a few 1:250 000 Sheet areas the existing data are of insufficient quality to allow conversion. These areas are shown blank in the accompanying magnetic imagery, but have recently been resurveyed by BMR in conjunction with the Geological Survey of New South Wales. An index map of the 1:250 000 Sheet areas showing the data coverage is shown in Figure 163.

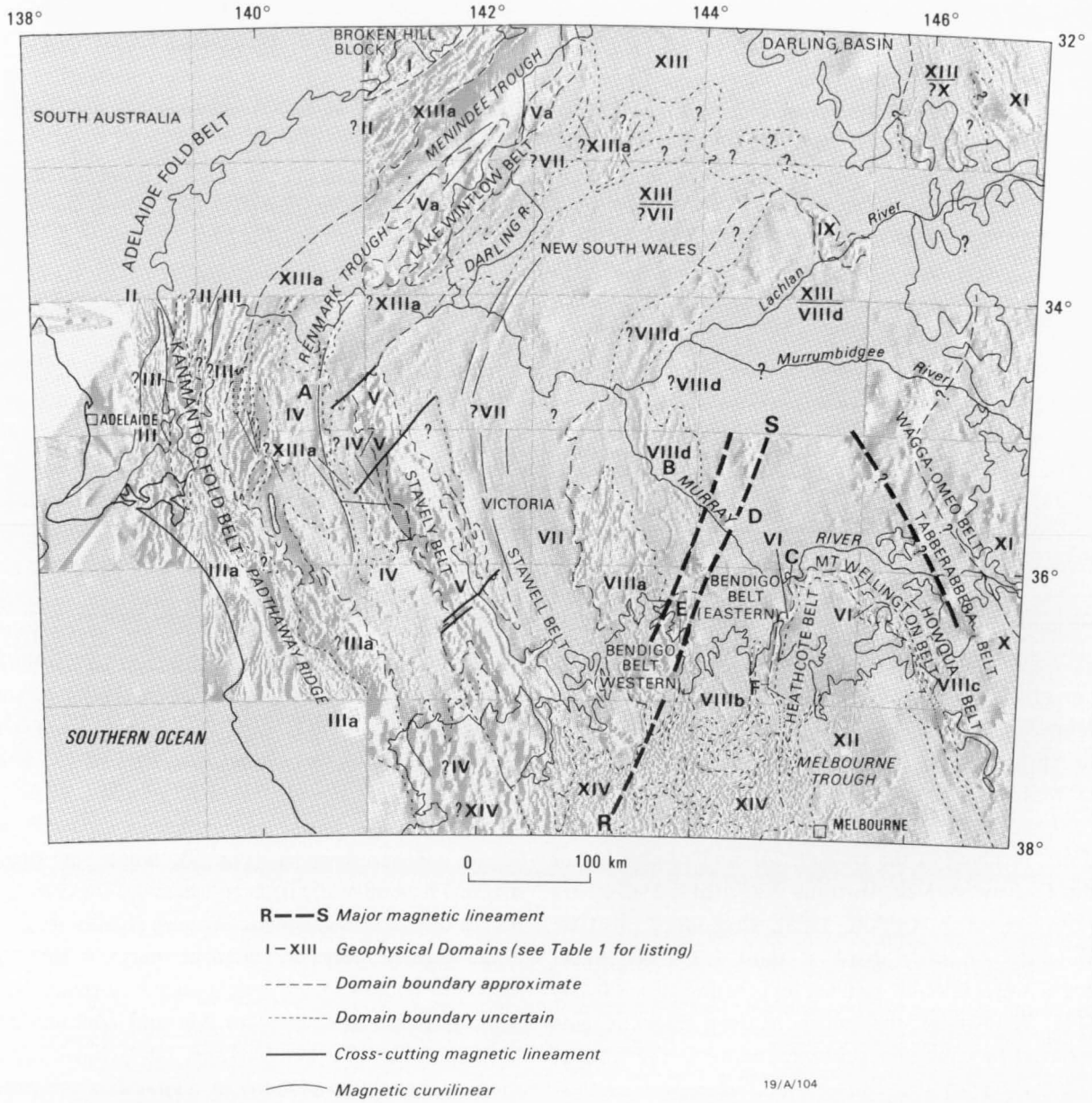

Fig. 162. Total magnetic intensity imagery with overlay showing boundary of Cainozoic Murray Basin, and location of interpreted geophysical Domains I–XIII (described in Table 2). Localities A–F are referred to in the accompanying text.

The definition of narrow width and high-gradient anomalies has been enhanced by calculating horizontal east–west gradients (Plate 16). This results in the appearance of a magnetic pseudo-topography for this mathematical entity. As discussed by Tucker & others (1985a), the combined effects of field inclination and azimuth, as well as body dip, strike, width and susceptibility, can result in complications which require that some caution be exercised if the imagery is to be interpreted in the same way as photography of topographic features. Despite these limitations, the magnetic imagery enhances the definition of basement features and structural trends.

Regional magnetic features

The aeromagnetic imagery (Plates 16, 17; Figs 161, 162) has improved the resolution of structural trends beneath the Murray Basin, as described below. However, the source of many magnetic anomalies remains unknown, and interpretation of basement features is at a preliminary stage. The following features can be seen on the imagery:

(1) Arcuate geophysical domains and curvilinear aeromagnetic trends: Several authors have previously attempted to correlate geological sequences exposed to the north of the Murray Basin with those exposed

to the south, and have extrapolated their interpretations beneath the basin (e.g. Webby, 1978; Cas & others, 1980; Cook, 1982; Powell, 1983). Most such interpretations have assumed that the northerly structural trends in the topographically elevated areas of the Lachlan Fold Belt to the east and south can be extrapolated beneath the basin. This assumption is only partly supported by the aeromagnetic imagery (Plates 16, 17) and Bouguer gravity data (see Fig. 20; Plate 15; also fig.4 of Wyatt & others, 1980), and the data can be interpreted in terms of a number of concealed arcuate magnetic domains, which are concave to the east (Figs 19, 162; Table 2). The arcuate configuration may be partly due to the intersection of fracture systems, or alternatively may indicate the presence of high-angle easterly dipping folded, and possibly thrust-faulted, metasedimentary rocks. Examples occur at locality 'A' and farther east at locality 'B' as shown on Figure 162.

(2) Adelaide and Kanmantoo Fold Belts: In the west, sigmoidal fold axes and arcuate ?thrust planes in metasediments of the Kanmantoo Fold Belt (Domain III), as well as ?ironstone horizons in sedimentary rocks of the Adelaide Fold Belt (Domain II), are well represented in the magnetic data. The curvilinear magnetic anomalies (Plates 16, 17; Fig. 162) may indicate the presence of arcuate, northwesterly and northeasterly trending, predominantly easterly dipping, high-angle folds and ?thrust-planes. These 'Adelaide' and 'Kanmantoo' structural features appear to extend beneath the western Murray Basin at least as far to the east as Domain IV (Fig. 162). The pattern of these curvilinear magnetic anomalies indicates a similarity of deformational style and a continuity of structural trend between the Adelaide (Domain II) and Kanmantoo (Domain III) Fold Belts. The pattern suggests that Adelaidean and Kanmantoo Fold Belts rocks may also extend beneath the western Murray Basin as far to the east as Domain IV. In addition, the metasediments of the ?Kanmantoo Fold Belt in the concealed Padthaway Ridge display a northwesterly trending structural grain and a possible partial continuity of structural trend with the rocks of the adjacent Mount Lofty Ranges, despite the pattern of uplift of the ranges to the southwest.

(3) Stavely, Lake Wintlow, Heathcote and Mount Wellington Greenstone Belts: The magnetic imagery contains linear belts of high total-magnetic intensity, some of which can be interpreted as distinct volcanic belts. In western Victoria, the ?Late Proterozoic–Cambrian volcanics and associated rock assemblages of the Stavely and Black Range areas (Figs 19, 162)

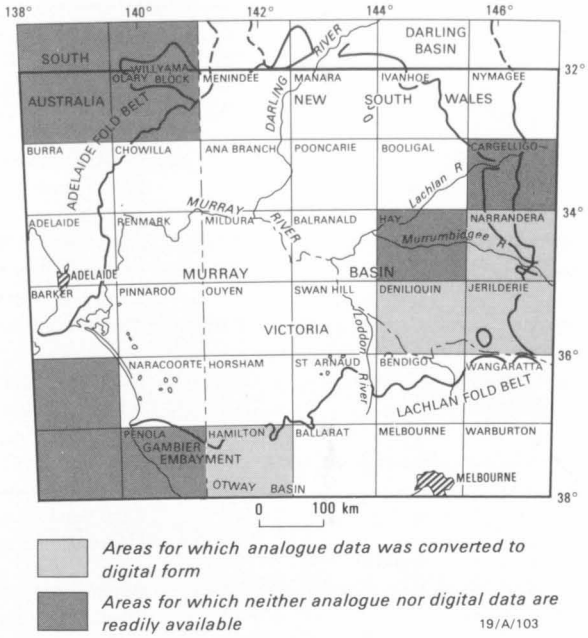

Fig. 163. Locality of total magnetic imagery shown on Figs. 161, 162 and accompanying Plates 16 and 17; with index of 1:250 000 map sheet areas.

appear to be components of a single strongly magnetic domain (Domain V). The Domain is 40 km wide and extends to the northwest for at least 400 km (Stavely Belt; Fig. 19). In western New South Wales, a similar but northeasterly-trending belt of high total-magnetic intensity (Domain Va) suggests that volcanics may also underlie parts of the Lake Victoria and Lake Wintlow Gravity Highs (Fig. 20; Lake Wintlow Belt). The interpreted volcanics are entirely concealed and they could be as young as Devonian, but the magnetic data suggest that they can be correlated with the Cambrian or older volcanics of the Stavely Belt to the south, and also with similar high intensity anomalies generated by the Cambrian Mount Wright Volcanics and ?Proterozoic–Cambrian Mount Arrowsmith Volcanics which are exposed to the north of the basin (Cook, 1982; Webby, 1982).

To the southeast of the Murray Basin, the northerly trending Heathcote and Mount Wellington Belts (Figs 19, 162) are represented by narrow linear zones of high magnetic intensity (Domain VI). The magnetic imagery indicates that the two greenstone belts are linked beneath the Murray Basin and that they possibly form parts of a single fault-disrupted sheet (e.g. locality 'C', Fig. 162; Brown & others, 1988).

(4) Cambrian to Devonian metasedimentary belts: The magnetic character of the ?Cambro–Ordovician Stawell Belt (Domain VII) is distinctly different from

TABLE 41. AEROMAGNETIC SURVEYS

Survey	*Year*	*Company*	*Reference*
Pinnaroo-Naracoorte-Renmark	1955/56	Murray Basin Oil	Murray Basin Oil (1960)
Olary-Chowilla	1955	S.A. Department of Mines & Energy	S.A. Department of Mines & Energy (1959)
Western Murray Basin	1955/61	Murray Basin Oil & Bureau of Mineral Resources, Australia	Seedsman (1964a)
Adelaide-Barker	1956	S.A. Department of Mines & Energy	S.A. Department of Mines & Energy (1961)
Murray River Basin	1956	Frome-Broken Hill Company Pty Ltd	Frome-Broken Hill (1956a,b)
Naracoorte-Penola	1957	S.A. Department of Mines & Energy	S.A. Department of Mines & Energy (1957)
Murray Basin (Wentworth)	1957	Australian Oil & Gas Corp. Ltd	Australian Oil & Gas (1957b)
Murray Basin	1957	Frome-Broken Hill Co. Pty Ltd	Frome-Broken Hill (1957b)
Western District (Vic.)	1957	Bureau of Mineral Resources, Australia	Wiebenga (1957)
Cobar-Nymagee-Cargelligo (Euabalong)	1957/58	Bureau of Mineral Resources, Australia	Spence (1961)
Broken Hill (N.W. Menindee)	1957/59	Bureau of Mineral Resources, Australia	Spence (1963)
Oaklands Basin	1960	Australian Oil & Gas Corp. Ltd	Australian Oil & Gas (1960a)
Burra	1960	Bureau of Mineral Resources, Australia	Wells (1962)
Chowilla	1961	Bureau of Mineral Resources, Australia	Young (1963)
Ivanhoe P.E.L. 51	1962	Adastra Geophysical Pty Ltd	Exploration Drilling (1962)
Menindee (Manara)	1962	Aero Service Ltd	North Australian Petroleum (1962)
Darling Depression (Menindee & Blantyre Troughs	1962/63	Planet Oil Co. Pty Ltd	Planet Oil (1962)
Murray Basin (central & S.W.)	1962/63	Bureau of Mineral Resources, Australia	Planet Exploration (1962a)
Murray Basin	1963	Planet Oil Co. N.L.	Crosby (1963)
Darnick Range (Manara)	1963	Aero Service Ltd	North Australian Petroleum (1963)
Echuca (Kerang-Wodonga-Shepparton)	1963	Adastra Hunting Geophysics Pty	Seismic Analysis Ltd (1963)
Bendigo-Wangaratta-Tallangatta	1972	Bureau of Mineral Resources, Australia	Downie & others (1976)
Ballarat	1974	Bureau of Mineral Resources, Australia	Bureau of Mineral Resources (1974a)
St.Arnaud	1974	Bureau of Mineral Resources, Australia	Bureau of Mineral Resources (1974b)
Horsham-Hamilton	1974	Bureau of Mineral Resources, Australia	Bureau of Mineral Resources (1974c)
Horsham	1980	Bureau of Mineral Resources, Australia	Bureau of Mineral Resources (1980)
Murray Basin	1980	CRA Exploration Pty Ltd	Bubner (1980)
Florieton area	1981	CRA Exploration Pty Ltd	CRA Exploration (1981)
Horsham	1982	CRA Exploration Pty Ltd	Richards (1982)
Barker-Punnaroo	1983	CSR Ltd.	Gidley (1983)
Magnetometer Survey	1986	N.S.W. Geological Institute	Stanley & Catach (1986)

that of the adjacent Ordovician Bendigo Belt to the east (Figs 19, 162). Beneath the southeastern Murray Basin and adjacent parts of the Victorian Highlands, the Ordovician metasediments of the Bendigo Trough (Fig. 19) can be subdivided into a number of zones with distinctive magnetic patterns. In the Victorian Highlands, for example, the Bendigo Trough can be divided into a western zone of magnetically complex Ordovician metasediments (Domain VIIIa), extensively metamorphosed and intruded by Lower and Upper Devonian batholiths having both magnetic and non-magnetic phases; and a relatively magnetically quiet eastern zone of Ordovician metasediments (Domain VIIIb), intruded only by non-magnetic Upper Devonian granitoids. Both zones are disrupted by northerly-trending magnetic lineaments which can be interpreted as faults. The concave-to-the-east configuration of the arcuate northerly trending magnetic lineaments beneath the Murray Basin may indicate westerly directed folding and thrust faulting, although alternative interpretations are possible.

Beneath the southeastern Murray Basin, the data reveal the presence of a synclinorial (or possibly anticlinorial) structural feature, where Ordovician sedimentary rocks flank the Siluro-Devonian sedimentary rocks of the Melbourne Trough. This feature apparently links the magnetically quiet Ordovician metasediments of the eastern Bendigo Trough (Domain VIIIb) with those of the Howqua Belt (Domain VIIIc). Magnetic discontinuities at the margins of the feature are intruded by lines of magnetic Devonian granitoids (e.g. cross-cutting magnetic lineament R-S on Figs 19, 162).

East of the Bendigo Belt, deformed Siluro-Devonian sedimentary rocks of the Melbourne Trough also form a distinctive magnetically quiet synclinorial (or possibly anticlinorial zone – Domain XII). These are flanked to the west and east by the highly magnetic Cambrian volcanics of the Heathcote and Mount Wellington Belts, further flanked by the magnetically quiet Ordovician metasediments of the eastern Bendigo and Howqua Belts. One possible explanation for this configuration is that the Melbourne

Trough and the flanking Cambrian volcanics and Ordovician metasediments represent remnants of allochthonous thrust sheets, and the older rocks were emplaced over the top of anticlinorial Melbourne Trough rocks. Alternatively, the Melbourne Trough was down-faulted form a fault-bounded synclinorium.

(5) Cross-cutting magnetic lineaments: The magnetic data reveal the widespread presence of an orthogonal pattern of cross-cutting linear discontinuities, which can be interpreted to represent a late-orogenic fracture pattern. The major lineament sets display a northeasterly or northwesterly orientation. Northeasterly lineaments, transected by minor northwesterly displacements, predominate beneath northern areas of the basin, whereas northwesterly trends off-set by cross-cutting northeasterly lineaments predominate beneath southern areas. Similar trends are also evident in the Bouguer gravity anomaly data (Fig. 20). In the northwest, for example, a major fault zone which approximates the Darling Lineament (Fig. 19) is marked by a major change in both magnetic and gravity character (Tucker, 1983).

(6) Granitoids: Granites have been encountered by petroleum exploration wells and water bores at several localities throughout the Murray Basin, but the distribution and extent of these bodies are poorly known. The magnetic data (in combination with gravity data) reveal the presence of a number of these large variably magnetic granitoids with associated magnetic contact metamorphic aureoles. An example of a non-magnetic granite with a magnetic contact aureole occurs at locality 'D' (Domain VIIIb, Fig. 162; Plate 17). A zone of multiple intrusion of both magnetic and non-magnetic granites is particularly well-developed at locality 'E' (Domain VIIIa).

(7) Pre-Cainozoic infrabasins: The magnetic data can be used to more clearly differentiate those areas of the Murray Basin underlain by shallow basement rocks from those underlain by thick Siluro-Devonian, Permian, and Cretaceous sediments (e.g. Menindee Trough; Domains XIII, XIIIa – Fig. 19). The data also suggest that the Upper Silurian–Devonian sediments of the Darling Basin to the north may be linked with those of the Grampians region to the south, via a number of these down-faulted and concealed infrabasins (Domain XIIIa; e.g. Netherby Trough – see Fig. 23).

(8) Tertiary volcanics: Tertiary volcanics display a characteristic pattern of speckled and linear magnetic anomalies (Domain XIV) over some areas of the Victorian Highlands. Valley-fill basalts also locally extend into the Murray Basin from the highlands (e.g. a northerly trending tongue of high magnetic intensity at locality 'F' on Fig. 162).

Data sources: Aeromagnetic surveys undertaken during the course of hydrocarbon exploration are listed on Table 41. Copies of completion reports from Commonwealth subsidised surveys are available for inspection at BMR, and additional unsubsidised survey reports are held in open file archives by the relevant State Mines Department. Contoured aeromagnetic maps produced at 1:250 000 are available from BMR (Fig. 7). Details of airborne magnetic surveys up to 1977 are recorded in BMR Report 204. Maps in the South Australian part of the basin are available from the South Australian Department of Mines and Energy. Reviews of aeromagnetic surveys undertaken in the South Australian part of the basin are given in Seedsman (1964a) and Thornton (1974), and surveys undertaken in northwestern areas, in New South Wales, have been reviewed by Bauer & others (1979), Byrnes (1985) and Sniffen (1985). Brown & others (1988) interpreted the magnetic imagery in terms of concealed structural belts and geophysical domains and discussed the implications of these interpretations for tectonic reconstructions of southeastern Australia.

Seismic

A large number of seismic refraction and reflection surveys have been undertaken by petroleum companies during exploration (Table 42). Unfortunately, most of the early surveys were undertaken in the 1960's, when data acquisition and processing techniques were not as sophisticated as at present. Consequently, the quality of seismic records of many of these early surveys is poor. Several of the older surveys involved short-length refraction profiles, used as an adjunct to gravity surveys to locate the margins of gravity-defined structural features. In addition, most of these early reflection surveys used analogue recording techniques. Activity was concentrated in and around the vicinity of the Renmark Trough, where a number of reflection and refraction seismic surveys established the configuration of the trough and the location of many of its bounding faults. Several reflectors were subsequently tested by drilling. Despite the poor quality of the early surveys, they confirmed the major sedimentary troughs beneath the northwestern Murray Basin, and subsequent reflection surveys have been mainly undertaken in this area.

TABLE 42. SEISMIC SURVEYS (page 1 of 2)

Survey	*Year*	*Area*	*Company*	*Reference*
Oaklands-Coorabin (refraction)	1949	Oaklands Basin	Bureau of Mineral Resources, Australia & Australian Oil & Gas Corporation Ltd	Thyer & Vale (1952)
Loxton S.A. (reflection)	1960	Vicinity of Loxton No.1 well	Hackathorn Oils Ltd	Denison & Denton (1960)
Loxton S.A. (refraction)	1960/61	Loxton	Hackathorn Oil Ltd	Hackathorn Oil (1962)
Murray Basin (refraction)	1960	Carrathool to Loxton	Bureau of Mineral Resources, Australia	Watson (1962)
S.W. Murray Basin (refraction)	1961	Padthaway Ridge to Loxton No.1 well	South Australian Department of Mines	Seedsman (1964a)
Oaklands-Jerilderie	1961	Oaklands Basin	Australian Oil & Gas Corporation Ltd & Bureau of Mineral Resources, Australia	Kaper (1961) & Petty Geophysical (1961)
Bunda-Lake Boga (refraction)	1962	Swan Hill-Deniliquin area	Woodside (Lakes Entrance) Oil Co. Pty Ltd	Warner & Miller (1962a)
Magenta-Hay (refraction)	1962	Hay-Balranald district & area to north	Planet Exploration Co. Pty Ltd	Warner & Miller (1962b)
Mildura (reflection)	1962	Hay-Mildura-Ouyen	Planet Exploration Co. Pty Ltd	Planet Exploration (1962b)
Oaklands Basin (reflection)	1962	Jerilderie	Australian Oil & Gas Corporation Ltd	Short (1961)
Stephens Creek (67 km refraction & reflection)	1962	Lake Wintlow High & Menindee Trough	General Geophysical Company	Alliance Oil (1962)
Wentworth (reflection)	1962	N. margin of Lake Victoria in Wentworth Trough	Australian Oil & Gas Corporation Ltd	Davis (1962)
Griffith (refraction)	1963	50 km S.W. of Griffith	Amalgamated Petroleum Exploration Pty Ltd	Kreitz & Weimar (1963)
Lake Pamamaroo (single-fold reflection)	1963	Lake Wintlow High	Geophysical Associates Pty Ltd	Alliance Oil (1963)
Lake Victoria (reflection)	1963	E. of Lake Victoria	Australian Oil & Gas Corporation Ltd	Harkness (1963)
Loxton S.A. (reflection)	1963	Renmark Trough	Beach Petroleum N.L.	Stackler & Yakunin (1962)
Murray Basin (reflection & refraction)	1963	Northern Murray Basin	South Australian Department of Mines & Energy	Seedsman (1963)
Murrayville-Casterton (reflection & refraction)	1963/63	Murrayville near Ouyen	Planet Exploration Co. Pty Ltd	Hightower & Hoffman (1963)
Oaklands-Jerilderie	1963		Amalgamated Petroleum Exploration Pty Ltd	
Murray Basin-Canegrass & Monash Lines (refraction)	1963/64	N.W. Murray Basin	South Australian Department of Mines & Energy	Kendall & Seedsman (1964)
Murray Basin seismic review	1964	Murray Basin	Australian Oil & Gas Corp. Ltd	Australian Oil & Gas (1964)
Central & southern part of western Murray Basin (refraction)	1965	Padthaway Ridge to Murray River	South Australian Department of Mines & Energy	Coppin (1967)
Nulla Nulla (refraction)	1965	N.W. Murray Basin near Tararra Homestead	South Australian Department of Mines & Energy for Australian Oil & Gas Corporation Ltd	Moorecroft (1965b)
Hyperna Line (refraction & reflection)	1965	N.W. Murray Basin, continuation of Nulla Nulla Line	South Australian Department of Mines & Energy for Australian Oil & Gas Corporation Ltd	Kendall (1965)
Pooncarie (refraction & reflection)	1965	Pooncarie area S. to Murray River	Namco Geophysical Co.	Australian Oil & Gas (1965b)
Renmark, South Australia (reflection)	1965	N. of Renmark	Tasman Oil Pty Ltd	Campbell (1965)
Tandou (refraction & single-fold reflection)	1966	Southern end of Menindee Trough	Petty Geophysical Engineering Co.	North Australian Petroleum (1966)
Deniliquin (refraction)	1966	S.E. Murray Basin (Deniliquin-Hay)	Australian Oil & Gas Corp.	Australian Oil & Gas (1966)
Ivanhoe (single fold reflection & refraction)	1966	Ivanhoe Trough	Namco Geophysical Co.	Exploration Drilling (1966) & NAMCO (1966)
Murray Basin Province, South Australia (refraction)	1966	Renmark-Loxton area	Beach Petroleum N.L.	Yakunin (1966)
Tararra (reflection)	1966	Tararra Trough	Australian Oil & Gas Corporation Ltd	Bowman (1966a)
South Tararra (refraction)	1966	Tararra Trough	Australian Oil & Gas Corporation Ltd	Bowman (1966b)
Hamley, South Australia	1967	North of Renmark	Associated Australian Oilfields N.L.	Associated Australian Oilfields (1968)

TABLE 42. ctd. (page 2 of 2)

Survey	*Year*	*Area*	*Company*	*Reference*
Reconnaissance refraction survey	1967	Central & southern Murray Basin in S.A.	South Australian Department of Mines and Energy	Coppin (1967)
Four Corners	1968	Darling River, near Menindee, S.W. to S.A. border	Alliance Oil Development Australia N.L.	Alliance (1968b)
Lake Wintlow (112 km single-fold reflection & 45 km refraction)	1968	Blantyre Trough, Lake Wintlow High & Menindee Trough	Geophysical Associates Pty Ltd	Alliance (1968c)
Tandou-Coombah (refraction & 142 km five-fold reflection)	1968	Southern end of Menindee Trough	Ray Geophysics (Australia) Ltd	North Australian Petroleum (1968)
Mildura & Broken Hill (deep crustal reflection)	1968	East of Mildura	Bureau of Mineral Resources, Australia	Branson & others (1972)
Hay	1969	Hay	Planet Exploration Co. Pty Ltd	Planet Exploration (1969b)
Hay, New South Wales (100 km refraction)	1969	About 50 km south of Hay in Killendoo Trough	Geophysical Service International	New South Wales Oil & Gas (1969b)
Mossgiel	1969	Near Booligal, New South Wales	Geophysical Service International	New South Wales Oil & Gas (1969c)
Nambucurra (140 km refraction)	1969	160 km south-east of Broken Hill in Wentworth Trough	New South Wales Oil & Gas Co. N.L.	New South Wales Oil & Gas (1969d)
Tandou-Redbank (37 km five-fold reflection)	1969	Southern Menindee Trough	Ray Geophysics (Australia) Ltd	North Australian Petroleum (1969)
Sunset (reflection)	1969	Eastern Renmark Trough, Victoria	Associated Australian Oilfields N.L.	Drew & others (1969)
Jerilderie North (60 km three-fold reflection)	1970	Oaklands Basin	New South Wales Oil & Gas Co. N.L.	New South Wales Oil & Gas (1970a)
Mount Emu (51 km three-fold & six-fold reflection)	1970	Blantyre Trough	Petty Geophysical Engineering Co.	New South Wales Oil & Gas (1970b)
Narweena (75 km reflection & refraction)	1970	East of Renmark Trough, over Lake Victoria High	Geophysical Associates Pty Ltd	Pexa (1970)
Menindee Regional (228 km six-fold reflection)	1973	Blantyre, Menindee & southern Bancannia Troughs	Beaver Exploration (Aust.) N.L.	Beaver (1973)
Jerilderie (reflection)	1977	north of Jerilderie	New South Wales Geological Survey	Palmer (1977)
Long range profile	1977	S.E. Australia		Muirhead & others (1977)
S.E. Australia explosion profiles	1979	S.E. Australia	Bureau of Mineral Resources, Australia	Finlayson & others (1979)
Nanda (reflection vibroseis 24-fold)	1981	Wentworth Trough	Comserv (No. 779) Pty Ltd	Comserv (1981a)
Byrnedale (Blackgate; reflection vibroseis 24-fold)	1981	Menindee Trough	Comserv (No.779) Pty Ltd	Comserv (1981b)
Mildura West	1981	W. MILDURA	Comserv (No. 779) Pty Ltd	Comserc (1981c) & Hargrove (1982)
Robinvale	1981	Robinvale	Comserv (No.779) Pty Ltd	Comserv (1981d)
Bulla Park	1982	Northern Murray Basin	Comserv (No.779) Pty Ltd	Comsev (1982a)
Colombo (reflection vibroseis 24-fold)	1983	Oaklands Basin	Meekatharra Minerals Pty Ltd	Meekatharra Minerals (1983)
Darling (reflection)	1983	Northern Murray Basin	BHP Petroleum Pty Ltd	BHP Petroleum (1983)
Murray Basin (reflection vibroseis 48-fold, & explosion 12-fold)	1983	W. Murray Basin	Esso Exploration & Production Australia Ltd	Esso Exploration (1983)
Popiltah survey	1985/86	Tararra Trough	Claremont Petroleum N.L. & Comserv (No.779)	Claremont Petroleum N.L. (1986) & Vale (1986)
Wilga road seismic refraction survey	1987	Murray Basin	New South Wales Department of Water Resources	Odins (1987a)
Wemen seismic refraction survey	1987	Murray Basin	New South Wales Department of Water Resources	Odins (1987b)

Seismic recordings have been hampered by shallow, faulted metasedimentary basement ridges, separating fault-bounded troughs with several kilometres of sedimentary section. Several recent surveys show good results from central areas of the troughs, but resolution deteriorates adjacent to the basement ridges owing to complex faulting. Despite this limitation, the surveys have confirmed several kilometres of section within some of the troughs beneath the northwestern Murray Basin. The thick Devonian continental sediments and Lower Devonian marine sediments, as well as Permian and Cretaceous sections has been confirmed by drilling (see Chapter 5), but the age and character of deeper reflectors remains unknown.

Reflection surveys: In the region of the Menindee

Trough, high-quality profiles were obtained by North Australian Petroleum (1969) during the Tandou No.2 (Redbank) reflection survey, and high-quality reflection data were subsequently acquired during a six-fold multiple stack reflection survey of the Menindee and Blantyre Troughs, undertaken by Beaver (1973). Interpreted sections from this survey were published by Evans (1977). Comserv (No.779) Pty Ltd shot high-quality digital, 24 fold stack reflection profiles using the vibroseis technique during the Nanda Survey over the Wentworth Trough (Comserv, 1981a), the Byrndale Survey over the Menindee Trough (Comserv, 1981b), and Mildura West (Comserv, 1981c) and Robinvale (Comserv, 1981d) Surveys in northwest Victoria. Esso (1983) obtained high-quality 48-fold-stack profiles of the Tararra and Menindee Troughs during their Murray Basin Survey, and BHP Petroleum (1983) also achieved good results from their Darling Survey, undertaken at the northern margins of the Murray Basin. The above surveys have mainly confirmed the gravity-defined graben-like troughs, but in the Wentworth Trough area the Murray Basin Survey, undertaken by Esso (1983), found some structural sagging of sediments but no bounding faults. The recent high-quality reflection surveys have confirmed that the thick succession of Devonian and younger rocks is broadly warped and is deformed only adjacent to fault systems, unlike tightly folded equivalent rocks farther east (e.g. Darling Basin).

Refraction surveys: A number of seismic reflection surveys have been undertaken over the Ovens Graben/Oaklands Basin region in the southeastern Murray Basin. These surveys have helped to define the limits of the Upper Permian Coorabin Coal Measures (Palmer, 1977; McIntyre, 1976). A recent high-quality reflection survey (by Meekatharra, 1983 – Colombo Survey) in northern areas of the infrabasin obtained good reflectors at the base of the Tertiary and within the Permian.

The New South Wales Department of Water Resources has also run a number of detailed shallow refraction surveys. These have proved to be of particular value where the configuration of basement features is thought to have influenced groundwater flow. Odins & others (1985) and Kellett (1989), for example, used seismic refraction profiles to confirm the configuration of the concealed Ivanhoe Block at the northwestern margin of the Riverine Plain.

Deep crustal refraction profiles obtained by BMR have confirmed an underlying thick continental crust. Branson & others (1972), for example, conducted a survey between Broken Hill and Mildura, and identified a layered crust with a calculated thickness of 31 km beneath Mildura – thickening to 38 km beneath Broken Hill. Beneath Mildura, they identified an upper 23 km thick layer with a crustal velocity of 6.1 km/sec, over a lower crustal layer with an interval velocity of 7.0 km/sec. Muirhead & others (1977) undertook a long-range, east–west oriented, seismic profile extending over 1200 km of southeast Australia. Beneath the Murray Basin, they interpreted a 35 km thick two-layer crust consisting of an upper 20 km with an estimated velocity of 6.15 km/sec and a lower 15 km thick crustal layer with a velocity of 6.75 km/sec. In adjacent elevated areas of the Lachlan Fold Belt, Finlayson & others (1979, 1980) indicated that the crust ranges in thickness from 40 km to in excess of 50 km.

Data sources: Seismic surveys by the petroleum industry are listed in Table 42. Copies of Commonwealth Government subsidised survey completion reports can be inspected at the Petroleum Resource Assessment Branch, BMR; additional industry reports from each of the three States are held in open file archives at the relevant State Mines Department. Refraction surveys by the New South Wales Department of Water Resources are recorded mainly in unpublished internal reports. Seismic activity, in the vicinity of the Renmark Trough in South Australia, has been reviewed by Seedsman (1964a) and Thornton (1974). Bauer & others (1979) reviewed the results of all seismic surveys up to 1973 in the New South Wales portion of the Murray Basin and adjacent areas of the Darling Basin and Bancannia Trough. Additional reviews are given in Sniffen (1985) and Byrnes (1985).

Radiometrics

Airborne spectrometer data from the western Murray Basin are available in the form of 1:250 000 contoured maps by the Geophysical Observatories and Mapping Branch, BMR (Fig. 7). Digital data were recorded from surveys flown at a continuous ground clearance of 150 m on flight lines flown east–west and 1500–3200 m apart. Much of the data can be correlated with surface drainage and geomorphic patterns. Many lakes, for example are delineated by near-zero radioactivity, whereas some adjacent shorelines are associated with radioactive anomalies – possibly reflecting the presence of active or fossil groundwater discharge deposits.

Data sources: Pre-1970 radiometric data are shown on aeromagnetic maps. Radiometric maps produced since 1970 are available as 1:250 000 dyelines from

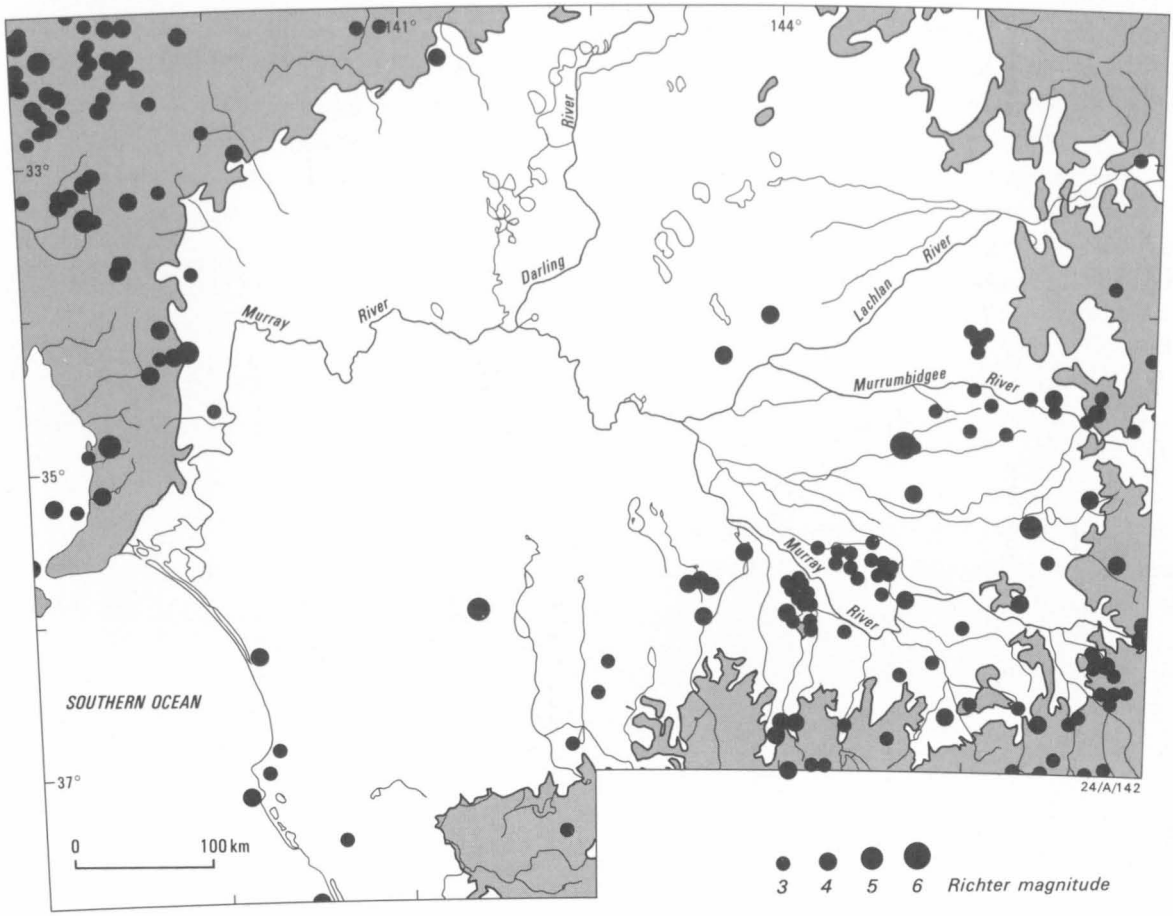

Fig. 164. Seismicity in the Murray Basin and adjacent areas between 1900 and 1987, showing epicentres of earthquakes with a magnitude of 3 or more on the Richter Scale. Data supplied by Australian Seismological Centre, Bureau of Mineral Resources.

the BMR Copy Service. In addition to contoured total radiometric counts, the potassium, thorium and uranium channels are available as separate contoured maps.

Magnetotellurics

The magnetotelluric method utilises weak fluctuations in the earth's magnetic fields, which induce telluric currents whose strength relates to the electrical resistivity of the rock section (Vozoff, 1972). The technique has been used to evaluate sediment thicknesses in the western Murray Basin. As noted previously, a major gravity low defining the Wentworth Trough is complicated by granitoids. Using the magneto-telluric method, Vozoff & Cull (1981) discriminated areas of shallow basement with gravity lows from areas of thick sediments with gravity lows. They calculated that the porous section is only 200 m thick and related this thin sequence to that encountered by NSW Oil & Gas Nambuccura No.1 (Haskell, 1970b). At the western margin of the Murray Basin, Dodds & Ivic (1985) used a combination of vertical electrical soundings (VES) and transient electromagnetics to estimate sediment thickness. The method proved to be successful in areas of relatively shallow basement.

Data sources: The methodology, techniques and results of magnetotelluric surveys in the Murray Basin are described in Vozoff & others (1975) and Vozoff & Cull (1981).

Seismicity

The Murray Basin is an area of relatively stable crust, and as shown on Figure 164, epicentres of seismic activity are mainly within the elevated fold belt and basement terranes at the western margins of the basin, reflecting recent uplift and continuing minor crustal adjustments. Minor activity has also been recorded in the adjacent Lachlan Fold Belt to the east, and extends beneath the eastern Murray Basin. Minor earthquakes have been recorded in adjacent offshore areas to the southwest of the basin.

Denham & others (1979) found that granite in a quarry near Tocumwal at the southeast margin of the basin was under sufficient crustal stress (20 MPa) to create 'pop-up' structures in the quarry floor. These stresses were found to be mainly horizontally directed and the observed maximum principal stresses are aligned approximately east–west. The measurements were made during the course of a survey, which investigated intraplate in-situ stress levels in the Australian crust.

Data sources: The earthquakes shown on Figure 164 were compiled from computerised earthquake data collected by the Australian Seismology Centre, Geophysical Observatories and Mapping Branch, BMR.

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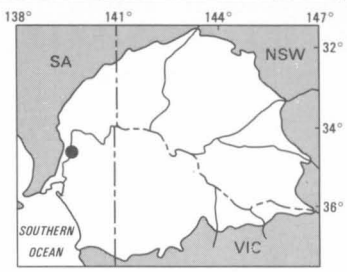

Fig. 165. Limestone cliffs of Murray River Gorge, near Blanchetown (photo taken from east bank looking downstream). The present-day gorge is thought to have formed during the Late Quaternary by down-cutting within the up-faulted Pinnaroo Block.

STRUCTURAL GEOLOGY

Basin geometry

The relatively thin Cainozoic sediments of the Murray Basin infill a shallow, low-lying, saucer-shaped basin, extending over 300 000 km^2 of inland southeast Australia. The basin is almost entirely flanked by subdued mountain ranges of Proterozoic and Palaeozoic fold belt rocks, except in the south-west, where shallow but largely concealed basement rocks of the coastal Padthaway Ridge (see Fig. 4 and Plate 3) form a southwestern rim to the groundwater basin, separating it from the Southern Ocean (see Chapter 4). Formation of the present-day basin is thought to have accompanied tectonic uplift of the flanking ranges in the Early Tertiary. Structure contours on the base of the Cainozoic sequence (see Fig. 4), indicate that the main depositional centre is located in central-western areas, where sediments occur at depths of around 500–600 m. In a subsidiary depositional centre, located beneath the west-central Riverine Plain, basal sediments occur at depths of around 300–400 m. Elsewhere, beneath northern, eastern and southern areas, the sediments are generally less than 200 m thick. Thicker sediments are locally preserved over some areas relative to others, as a consequence of minor differential subsidence of the underlying basement, resulting in

variations in basin geometry. However, despite the great extent of the Murray Basin, the sedimentary sequence is extremely thin, and in terms of basin geometry, consists of a thin veneer of platform-cover sediments rather than a 'conventional' basinal succession. The basin overlies an extensive area of tectonically deformed, but generally stable, basement crust. Subtle basement movements within the basement have, however, had a major influence on Cainozoic sedimentation, as well as on present-day groundwater flow and surface discharge patterns.

Basement structural trends and fracture patterns

The location of the major depocentres, and the overall geometry of the Murray Basin, have been determined largely by the structural configuration of the underlying basement. Regional aeromagnetic and gravity data indicate that the Cainozoic sequence of the Murray Basin is underlain by a composite collage of northerly trending (arcuate – concave to the east), Proterozoic–Palaeozoic tectonostratigraphic terranes and remnant Late Palaeozoic–Mesozoic infrabasins (see Chapters 4 and 12; Brown & others, 1982, 1988). Differential subsidence, and local uplift, of these underlying pre-Cainozoic elements are responsible for the variations in the geometry of the sediment fill of the basin. The arcuate structural trends are concave to the east and trend predominantly to the north-northwest beneath the southern part of the basin, and trend to the north-northeast beneath the northern Murray Basin (see Fig. 162). These trends are parallel to structural trends seen in outcrop in the adjacent Adelaide and Kanmantoo Fold Belts to the west. The northwesterly trends beneath the southern Murray Basin are also parallel to structural trends in adjacent elevated areas of the Lachlan Fold Belt in the Victorian Highlands to the south, but the predominant northeasterly trends beneath northern areas contrast with the north-northwesterly structural grain exposed in the Lachlan Fold Belt (see Fig. 19) to the east of the basin, as illustrated by the regional geological and tectonic maps of Pogson (1972) and Scheibner (1974). As discussed by Brown & others (1988), this suggests the likely presence of a major concealed structural discontinuity between basement elements underlying the Murray Basin and those of the Lachlan Fold Belt to the east. A similar structural discontinuity is seen in the exposed areas of the Siluro-Devonian Darling Basin at the northern boundary of the Murray Basin, where structures trend to the northeast, again in contrast to north-northwesterly trends in the adjacent components of the Lachlan Fold Belt farther east.

The basement beneath the Murray Basin is also strongly deformed by northerly fold and fault trends, such as those in the exposed basement areas of ST. ARNAUD, BENDIGO and WANGARATTA. These are cross-cut by basin-wide northeast-southwest and northwest-southeast fracture sets of ?Devonian age – resulting in the development of a mosaic of structural blocks (e.g. Firman, 1970b, 1974). Beneath southern areas, for example, the older northwesterly structural belts are disrupted by the younger northeasterly trending faults, such as the Danyo Fault (see Fig. 4), whereas the Pinnaroo Block is uplifted to the southwest side of the northwesterly trending Murrayville Fault. Similarly, beneath northern areas, the younger fractures partly emphasise older northeasterly trending fractures, and are partly disrupted by northwesterly trending fractures.

Subtle re-activation of the above basement fracture patterns, as well as differential subsidence over the underlying infrabasins relative to underlying structural rises, are reflected in Cainozoic sedimentation patterns, groundwater flow patterns, modern surface drainage patterns, and the distribution of surface geomorphic features. Rivers in the north drain to the southwest, and those in the south drain to the north-northwest. In the northwest, the course of the Darling River, and the distribution of the associated Menindee Lakes, reflect the orientation of the concealed Menindee Trough, whereas the lower Darling River overlies the Wentworth Trough. The shape of the modern Riverine Plain, and the convergence of surface drainage towards its central-western apex in the geographic centre of the basin (see Fig. 14), have been strongly influenced by the configuration of basement ridges concealed beneath its western margins (see Fig. 4). The main trunk stream of the basin – the Murray River – bisects the arcuate intersection between the concealed northwesterly and northeasterly trending structural belts, and flows over this intersection zone to the western margin of the basin, where it is defeated by the up-faulted Mount Lofty Ranges and turns abruptly to the south (Stephenson & Brown, 1989). Major bends in the course of the Murray River have also been found to reflect the presence of concealed basement faults and ridges. One of the most prominent and best documented of these occurs in the east, where reactivation of the northerly trending Cadell Fault has been accompanied by uplift of the

Cadell Block, resulting in flow disruption and ponding of the Murray River (see also 'Riverine Plain' and 'Coonambidgal Formation'). Part of the river flows to the north to form the Edwards River distributary, and part is deflected around the southern margin of the block. A triangular-shaped area of ponded drainage occurs to the east, forming the Barmah swamp forest (see Fig. 16). Recent uplift is indicated by the stranding of former fluvial channels of the Shepparton Formation to the west of the Cadell Fault (Pels, 1971; Bowler, 1978a).

Concealed infrabasins and structural highs

Beneath the basin, block-faulted basement rises are separated by fault-bounded graben-like troughs and downwarped infrabasins with Devonian and younger sediments (Chapter 5.). These include the Renmark, Tararra, and Menindee Troughs in the northwest, as well as the Oaklands Basin over the fault-bounded Ovens Graben beneath the southeastern Murray Basin (see Fig. 23). The bounding faults have been identified mainly on seismic sections (e.g. the Hamley Fault at the northwest margin of the Renmark Trough). The presence of other gravity-defined troughs, such as the Blantyre, Wentworth, Ivanhoe, and Netherby Troughs, has been confirmed by drilling, but these are less well-defined, and the locations of their boundaries are uncertain.

The basement rocks of the coastal Padthaway Ridge form the southwestern margin of the groundwater basin. The ridge has been partly up-faulted along the Kanawinka Fault. Farther to the northwest, the southwest margin of the elevated Pinnaroo Block is taken as the Marmon Jabuk Fault (Twidale & others, 1978), and the northeastern margin is taken as the Murrayville Monocline. Both these bounding faults have also influenced the course of the Murray River. The Murray River Gorge at the western margin of the basin was eroded into Miocene limestone during Late Quaternary periods of low sea-level, following Late Cainozoic uplift of the Pinnaroo Block. Firman (1970b) identified a mosaic of rectilinear fractures many of which influence the course of the Murray River. Faults which have influenced the shape of the western margin of the basin include the Encounter, Florieton, and Morgan Faults, whereas the northwest margin is controlled by the Anabama-Redan Fault zone, west of the 'Darling Lineament' (Fig. 19). Quaternary uplift of the ranges which flank the northwest margin of the basin, is reflected in the deposition of Quaternary fanglomerates and associated sediments of the Pooraka Formation in a broad zone of low-angle alluvial and colluvial aprons. Post-Miocene uplift of the Mount Lofty Ranges is indicated in the Myponga Basin within the ranges, where the top of the Miocene limestone occurs at an elevation some 150 m above the general level of the top of the Murray Group limestone of the Pinnaroo Block, in turn elevated relative to the top of the Murray Group in the adjacent Renmark Trough.

In western Victoria (HORSHAM), Lawrence (1966, 1975) and Lawrence & Abele (1976, 1988) have described the influence of the northwesterly trending Hindmarsh Fault zone on the distribution of Tertiary facies; with thick Ettrick Formation and Duddo Limestone (Tml) in the west being abruptly replaced to the east by thick Geera Clay and Winnambool Formation. The influence of many concealed faults extends to the surface. The cross-cutting northeasterly trending Danyo Fault finds surface expression in a number of groundwater discharge complexes (including Raak Plains; Macumber, 1980), where aquifer geometry and groundwater flow have been disrupted by the fault. Farther to the east, the northerly trending Tyrrell Fault is flanked to the west by shallow basement and to the east by the down-faulted Tyrrell Basin (see Fig. 4). The presence of the fault is thought to have contributed to development of Lake Tyrrell, and a northern extension of the fault zone can be traced to the Murray River.

The northwest margin of the Riverine Plain is flanked by the concealed eastern limb of the northeasterly trending Ivanhoe Block (see Fig. 4), whereas the Willandra Trough is confined to a narrow elongate structural depression within the basement rise – flanked to the west by the Neckarboo Ridge and to the east by the Iona Ridge. The Ivanhoe Block finds surface expression in northeasterly trending topographic ridges, which define the concealed northwestern (Neckarboo Ridge) and southeastern (Iona Ridge) margins of the block. These are locally elevated to heights of up to 120 m, whereas the Darling River to the west occurs at an elevation of less than 40 m, and the Riverine Plain to the southeast is at about 80 m. The presence of the up-faulted Ivanhoe Block has been confirmed by seismic refraction profiles and drilling, but several other gravity-defined 'highs', such has the Lake Wintlow gravity high (see Fig. 20), have not yet been confirmed as basement ridges.

Landsat lineament analysis (by W.J. Perry)

The surface of the Murray Basin was studied by reference to Landsat 1:1 million colour composite diapositives (Table 43), some 1:500 000 band 5 prints, a mosaic of band 5 1:1 million scale prints, and selected small-scale aerial photographs. Lineament annotations were made on two separate occasions some months apart. Fresh overlays were used in the later study, and only those features common to both studies are shown on the accompanying 1:1 000 000 geological map. Annotated features were compiled on an overlay of the Landsat mosaic. Curvilinear trends interpreted as former strand lines were recognised on the various Landsat products and then checked on aerial photographs.

During the interpretation, reference was made to structural elements of the pre-Murray Basin sequence (Thornton, 1972, fig. 2b), previously mapped faults, steep gravity gradients, and to the edges of areas of relatively high magnetic intensity. It is evident that a long north-northeast gravity trend correlates well with the western edge of the Renmark Trough, and it is assumed that the gravity trends elsewhere reflect structures in the pre-Tertiary rocks. For example, the trends extending north-northwest from the Silurian to Early Devonian sedimentary rocks of the Grampians probably represent a northerly extension of these rocks beneath the Tertiary cover. The sub-parallel zone of high magnetic intensity to the west of the gravity trends is probably due to the effect of Cambrian ultrabasic rocks.

Lineaments evident on the 1:1 million mosaic are mainly straight stream segments, the most striking of which is the well-known Darling River Lineament (Hills, 1961, his p.82; Scheibner, 1976, his p.122); this trends 50° east of north, and if a lineament parallel to the river is included, the feature is a corridor some 50 km wide. Rudd (1961) referred to a possible northeasterly extension, which he suggested might separate the deeper part of the Mesozoic Surat Basin sediments in Queensland from the shallower part in New South Wales, and cause an offset in the continental shelf. A depth-to-basement contour map of the Surat Basin (Exon, 1977, his plate 9), shows a deflection in strike of the contours from 800 to 3200 m on the northeast along the direction of the lineament, and a deflection in the 1100 to 1500 m contours in the southwest. O'Driscoll & Keenihan (1980) ascribe to the Darling River Lineament a Mesozoic embayment in the southwest of the basin,

TABLE 43. MURRAY BASIN LANDSAT-2 COLOUR COMPOSITE TRANSPARENCIES (17 SCENES)

Path/Row	*Date*
99/83	11/5/81
99-84	11/5/81
99-85	11/5/81
100/82	12/5/81
100-83	12/5/81
100/84	12/5/81
100/85	12/5/81
101/82	12/5/81
101/83	12/5/81
101/84	12/5/81
101/85	12/5/81
102/82	14/5/81
102/83	15/11/80
102/84	8/4/81
102/85	17/8/80
103/83	9/4/81
103/84	9/4/81

and in the northeast a conspicuous deflection in strike. They continue the Lineament to the head of St. Vincent Gulf in the southwest, but there appears to be no evidence of this on the Landsat imagery. However, the Total-magnetic intensity image (Figs 19, 162; Plates 16, 17) shows a possible continuation (pattern discontinuity) that crosses the coastline at the head of Encounter Bay on the east side of the Fleurieu Peninsula (c.f. section on Adelaide and Kanmantoo Fold Belts in 'Aeromagnetics').

A sub-parallel trend is shown by the lower reaches of the Darling River between Pooncarie and its junction with the Murray at Wentworth. The Darling River northeast of the Menindee Lakes appears to be structurally controlled locally, where several straight short segments trend alternately east by north and north by east.

The Edward River west of the Cadell Fault follows a generally west-northwest course that is probably structurally controlled; this is called the Murray River lineament by Scheibner (revision of 1973 Structural Map of New South Wales 1:1 000 000 scale, unpublished). A northwest-trending lineament corridor along the course of the Murray River, west of the Cadell Fault, converges with Scheibner's Murray River lineament in the vicinity of Robinvale. Neither lineament is evident on the aeromagnetic images.

Another group of lineaments, interpreted mainly from Landsat colour composite diapositives is shown by opposing arrows. This group shows two basic trends – northeast to north-northeast and northwest to north-northwest. The significance of these features is not clear; some are tonal alignments and therefore are showing changes in surface cover, including

vegetation; however, their relative straightness suggests underlying structural control rather than the expression of contacts between Holocene units.

Other lineaments have been annotated by viewing the Landsat mosaic at a low angle from various directions in turn. The more prominent of these lineaments trend about north-northeast. They may have some relationship with O'Driscoll's Broken Hill – Bendigo corridor (O'Driscoll, 1982, his fig. 38) because they display a sub-parallel trend, have a similar location, and cut across the northeast-trending gravity features. O'Driscoll (1982, his p.30) suggests that his pattern discontinuities or structural tracks "are deep crustal fractures operative through time as loci of high-energy transfer, which give access to igneous and volcanic activity, and which are the deep foundations that control sedimentary processes and basin development."

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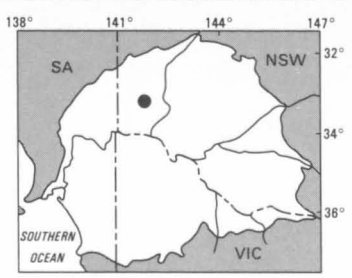


Fig. 166. Deflated Upper Pleistocene lunette, eastern margin of Yelta Lake, near Darling Anabranch (ANABRANCH). Layers within such lunettes contain a record of past fluctuations of the groundwater table and palaeoclimatic conditions over approximately the past 0.5 Ma.

GEOLOGICAL HISTORY

The Murray Basin developed in the Cainozoic, following the break-up between Antarctica and the southern margin of Australia in the Late Mesozoic–Early Cainozoic (e.g. Deighton & others, 1976; Cande & Mutter, 1982). The tectonic framework, which formed at that time, has provided the primary control on the stratigraphic development of the Murray Basin. However, the pre-Cainozoic tectonic elements underlying the Murray Basin form a tectonically stable platform, and the Cainozoic history of the basin has been characterised by slow tectonic subsidence rates. It has also been characterised by minimal compaction rates, and low rates of sediment supply and/or preservation. Consequently, the evolution of the Cainozoic stratigraphic framework of the basin also reflects the interactions between superimposed secondary tectonic, eustatic, and palaeoclimatic influences. Subtle tectonic movements, for example, have strongly influenced sedimentation patterns. However, depositional surfaces have tended to be topographically low-lying and of low gradient throughout the Cainozoic, and the basin has been particularly susceptible to partial flooding by shallow epicontinental seas during periods of high relative sea-level. Consequently, much of the sedimentary record of the basin is one of fluctuation in sea-level. Deposition of laterally extensive sequences of intercalated fluvio-deltaic, paralic and shallow-marine sediments correlates with major periods of high global sea-level, whereas periods of erosion or lack of preservation of sediments correlate with major periods of lowered sea-level. Within the Tertiary sequence at least three major depositional sequences of Tertiary age have been identified, each consisting of a distinctive package of related formations – Paleocene–Lower Oligocene (mainly Eocene), Oligocene–Middle Miocene, and Upper Miocene–Pliocene (Fig. 167; Brown, 1983, 1985). A number of minor transgressive–regressive marine cycles occur within each of the depositional sequen-

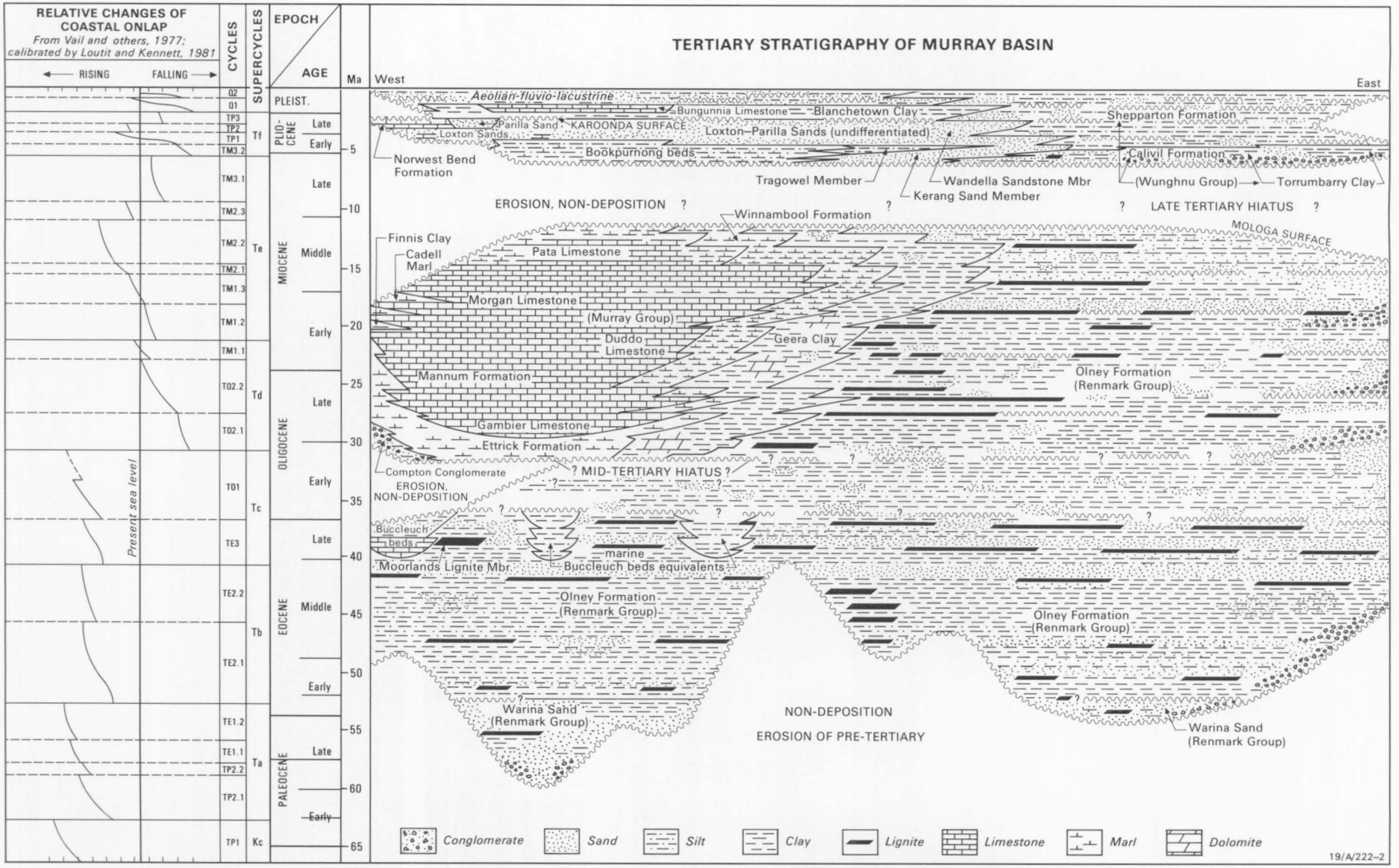


Fig. 167. Stratigraphy of Murray Basin with relative coastal onlap curve of Vail & others (1977), based on modification by Loutit & Kennett (1981).

ces. Non-marine silt, sand, clay, and carbonaceous sediments predominate in the east and north, but each major sequence includes marine to paralic sediments in southwestern to central areas. The lower sequence is characterised by a predominance of non-marine carbonaceous sediments, the middle sequence by development of a carbonate platform succession, whereas the upper sequence is characterised by development of a marine siliclastic shelf. Within each of the depositional sequences, palaeoclimatic factors have also influenced fluvial discharge, rates of sediment supply and sediment type.

Cainozoic sedimentation patterns — tectonic, eustatic and palaeoclimatic influences

Tectonic influences. The shallow-marine and fluvial sediments of the Tertiary succession form an extensive (300 000 km^2) but relatively thin cover, with a maximum thickness of 500–600 m within the deeper, west-central depocentre of the basin, and between 300–400 m of sediment within the Riverine Plain depocentre (see Fig. 4; Plate 4). Beneath northern, eastern, and southern areas, the succession is generally less than 200 m thick. Within this very thin sequence, subtle movements on basement faults have therefore had a considerable influence on the geometry and pattern of Cainozoic sedimentation, as well as on groundwater flow and surface discharge patterns. Thickness variations within the basin can be explained in terms of slight differential tectonic subsidence, and uplift of underlying basement elements.

It has previously been suggested that an ancient Murray River once extended across the present line of the Mount Lofty Ranges, and emptied into Spencer Gulf at various times in the Tertiary (Williams & Goode, 1978; Goode & Williams, 1980). A number of authors have disputed this possibility (e.g. Gostin & Jenkins, 1980; Harris & others, 1980). As discussed by Stephenson & Brown (1989), it seems likely that a topographically elevated western margin to the Murray Basin has existed throughout the Tertiary, albeit lower than that of the present.

Jones & Veevers (1982) proposed a model of regional tectonic cycles to account for the Tertiary depositional sequences of the Murray Basin. They suggested that subsidence and sedimentation occurred in the basin as a consequence of periods of uplift and Cainozoic volcanism in the adjacent southeast highlands, and that non-depositional hiatuses can be correlated with uplift and erosion of the basin accompanied by tectonic settling and volcanic quiescence in the highlands. In contrast, Ollier (1982) suggested that the detailed chronology of uplift history of the eastern highlands is currently not well understood, and proposed an alternative rift-valley model to explain uplift and geomorphic development of the coastal escarpment of the southeast highlands during the last 80 Ma. Whilst framework tectonics have clearly provided the primary control on sedimentation in the Murray Basin, it also seems likely that development of the depositional sequences, and fluctuations in the type, supply, and preservation of sediment in the Murray Basin have been sensitive to secondary eustatic (or tectono–eustatic) and climatic influences — and to consequent fluctuations in the erosive and depositional potential of the fluvial systems that traversed the basin (Brown, 1983, 1985).

Eustatic influences. Depositional sequences in the basin show an apparent correlation with the global supercycles of relative coastal onlap and offlap (i.e. relative rise and fall in sea-level) as published by Vail & others (1977), Vail & Hardenbol (1979), Vail & Mitchum (1979), Haq & others (1987), and calibration of Loutit & Kennett (1981) — these may be tectono–eustatic in character rather than simply eustatic. The basal depositional sequence was characteristically carbonaceous and non-marine, although a minor marine invasion took place in the Late Eocene–Early Oligocene. A sustained late Early Oligocene to Middle Miocene period of marine invasion of the Murray Basin, accompanied by a number of minor transgressive–regressive fluctuations in relative sea-level, is well recorded in the middle depositional sequence, and was associated with development of a carbonate platform. Evidence for an underlying Early Oligocene stratal break, corresponding to a major global fall in relative sea-level, is less certain, and the extent and duration of this event are poorly known. In addition, micropalaeontological age determinations from the base of the marine Oligo-Miocene Murray Group sequence suggest that the major marine transgression occurred in the late Early Oligocene, rather than the early Late Oligocene, which would be expected from correlation with the global coastal onlap curves. A further marine invasion, resulting in deposition of siliclastic sediments occurred in the Late Miocene–Pliocene. Within each of these major depositional packages, detailed cycles and sequences have been identified only locally and incompletely (e.g. Lindsay, 1983a). However, the succession of the Murray Basin, is relatively thin and probably incomplete.

The Cainozoic sequence of the Murray Basin does not overlie a uniform basement, but onlaps a composite collage of Proterozoic–Palaeozoic tectonostratigraphic terranes and Upper Palaeozoic–Mesozoic infrabasins. These have been characterised mainly by slight differential subsidence and uplift along pre-existing Devonian and older fracture sets. Consequently, the shape of the Murray Basin, as well as variations in sediment thickness, facies distribution, and present-day surface and groundwater drainage patterns, have been influenced by the structural configuration of the underlying basement (Chapter 4), as well as by local tectonic movements within it. However, despite these tectonic influences, each of the three Tertiary depositional sequences forms an extensive but thin and remarkably continuous blanket of sediment, extending over underlying tectonic boundaries. The basin succession was therefore deposited over a topographically flat, low-lying, and tectonically stable platform that was susceptible to partial flooding by epicontinental seas. It seems likely that deposition of laterally extensive packages of intercalated fluvio-deltaic, paralic, and shallow-marine sediments correlated with major periods of high global sea-level, whereas non-preservation because of erosion/non-deposition appears to correlate with periods of lowered sea level. It should be noted, however, that the development of the sequences of the Murray Basin reflects an interplay between rates of tectonic, eustatic and climatic change, and are not simply due to changes in global sea-level.

Climatic influences. Palynological studies have indicated that the Murray Basin was covered by forest for most of the Cainozoic. Spore and pollen assemblages, as well as the abundance of carbonaceous material in sediments of Eocene age, reflect interpreted year-round warm and humid climatic conditions. In the Miocene, the foramol fossil assemblages (temperate water skeletal grain association of Lees, 1975) in the carbonates of the southwest suggest a temperate climate with only minor extra-tropical incursions of warm water (McGowran, 1978b; James & Bone, 1988). However, palynological assemblages from carbonaceous Miocene sediments to the east and north suggest humid, although increasingly seasonal conditions (e.g. Martin, 1977; Truswell & others, 1985). Rainfall is thought to have become increasingly seasonal in the Late Cainozoic (Bowler, 1982), and resulted in a change in the forest cover, to extensive eucalypts (Truswell & others, 1985; Macphail & Truswell, 1989; Martin, 1989). Bishop (1985) attributed low rates of Tertiary erosion of the southeast highlands, and of sediment input to the Murray Basin, to a forest cover present throughout most of the Tertiary.

In the Late Pliocene–Early Pleistocene, when much of the western Murray Basin was covered by Lake Bungunnia, conditions were considerably wetter than of the present day (Stephenson, 1986), and there is no evidence of arid conditions in the geological record prior to the Late Pleistocene. It is only during the past 0.4 to 0.7 Ma that arid to semi-arid conditions have prevailed (e.g. Bowler, 1988). Palynological assemblages from lake floors in the Murray Basin show an alternation between predominance of woodland and grassland vegetation types during this Late Quaternary period. A record of past episodes of both arid and semi-arid climatic conditions is preserved in the characteristic Upper Quaternary landforms of the modern landscape of the Murray Basin.

Paleocene–Eocene–Lower Oligocene sequence

Sedimentation commenced in the Murray Basin about 60 Ma ago when weakly consolidated medium to coarse quartz sand of ?Paleocene–Eocene age was deposited in the deeper central-western depocentre of the basin (Fig. 168a; Tew – Warina Sand of the Renmark Group). In this area, the unit is locally up to 200 m thick, and infills down-faulted troughs and irregularities in an otherwise relatively flat pre-Cainozoic topography. Thinner basal sand of uncertain age, which underlies west-central areas of the Riverine Plain, was also tentatively assigned to the Warina Sand by Woolley & Williams (1978). Borehole logs indicate that the unit consists mainly of stacked massive sand bodies that coalesce to form a sand sheet, thought to have been deposited in a mainly fluviatile, ?braided-channel environment. Minor thin lenticular intercalations of fine-grained sand, silt and clay were deposited in lacustrine and flood-plain environments. These intercalations are commonly highly carbonaceous, with abundant pyritised wood, but are often only a few centimetres thick.

Deposition of the coarse clastics of the Warina Sand was followed in the Eocene by that of an extensive, lithologically variable blanket of laterally discontinuous, unconsolidated to poorly consolidated, carbonaceous silt, sand, and clay, with common interbeds of lignitic coal and peat (Fig. 168b; Teo – Olney Formation of the Renmark Group). These were deposited in mainly fluvio-

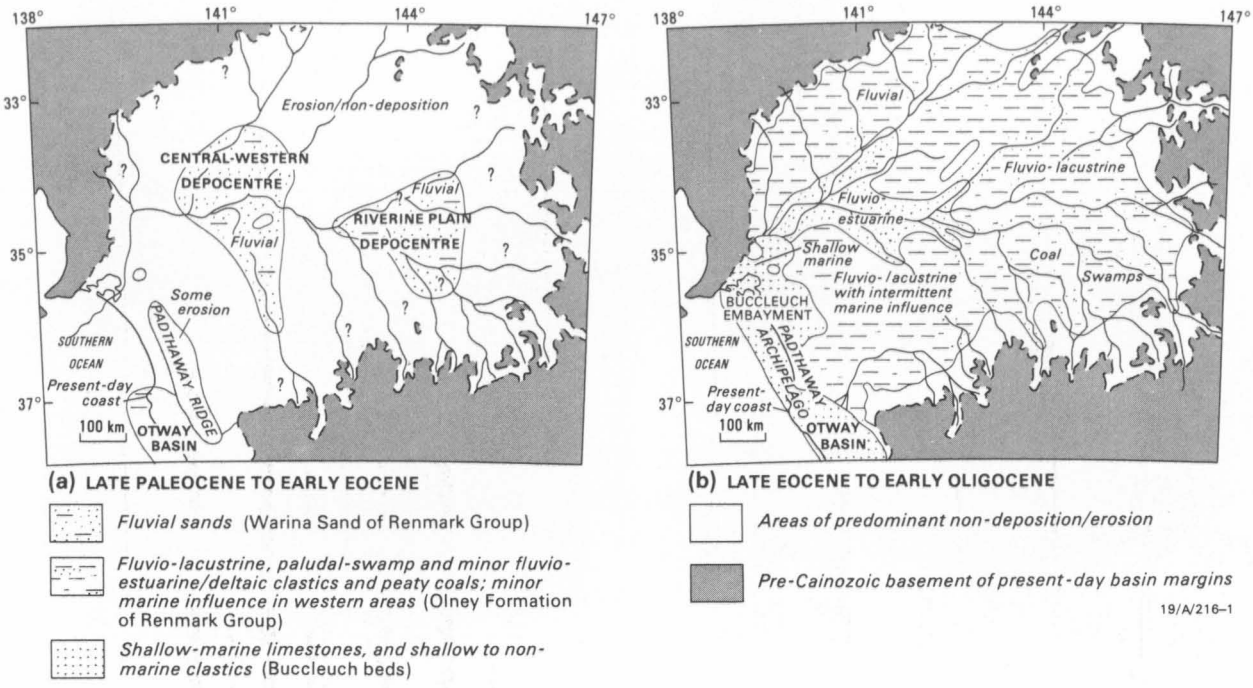
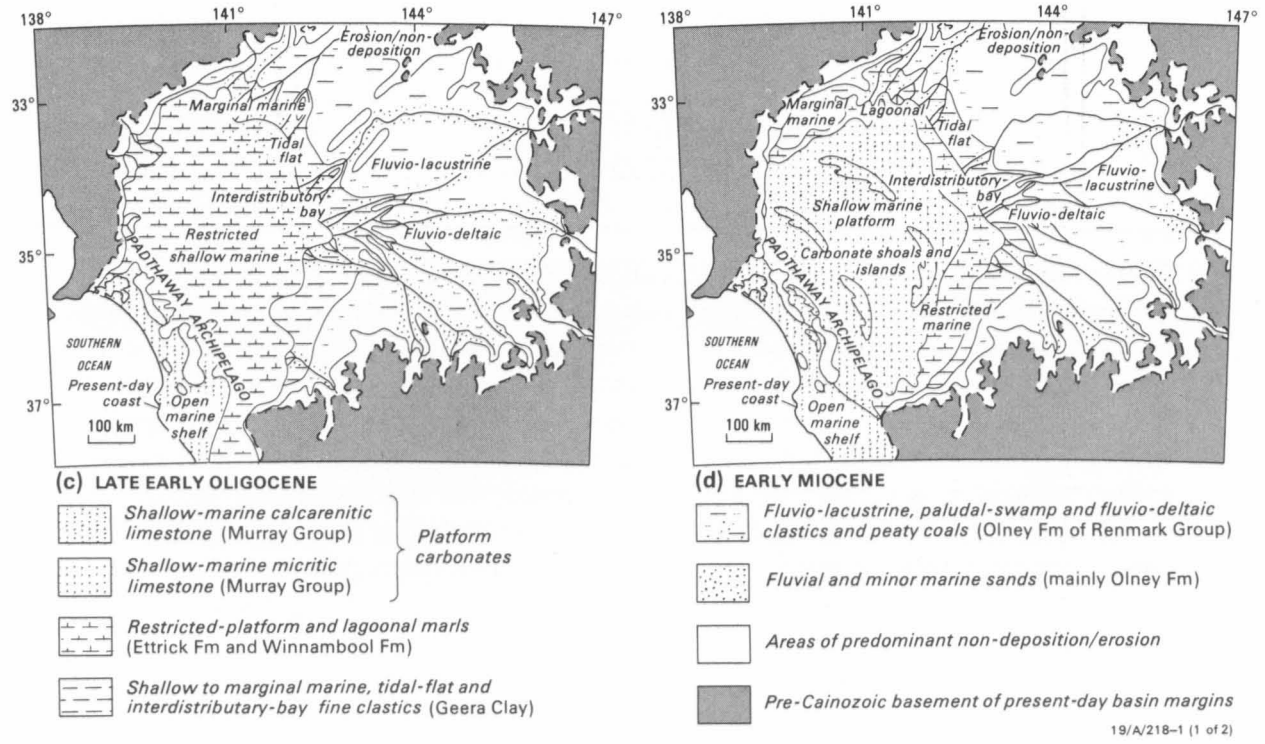


Fig. 168. Tertiary palaeogeography of the Murray Basin: (a) Late Paleocene to Early Eocene; (b) Late Eocene to Early Oligocene; (c) Late Early Oligocene; (d) Early Miocene; (e) Late Miocene to Early Pliocene; (f) Pliocene.



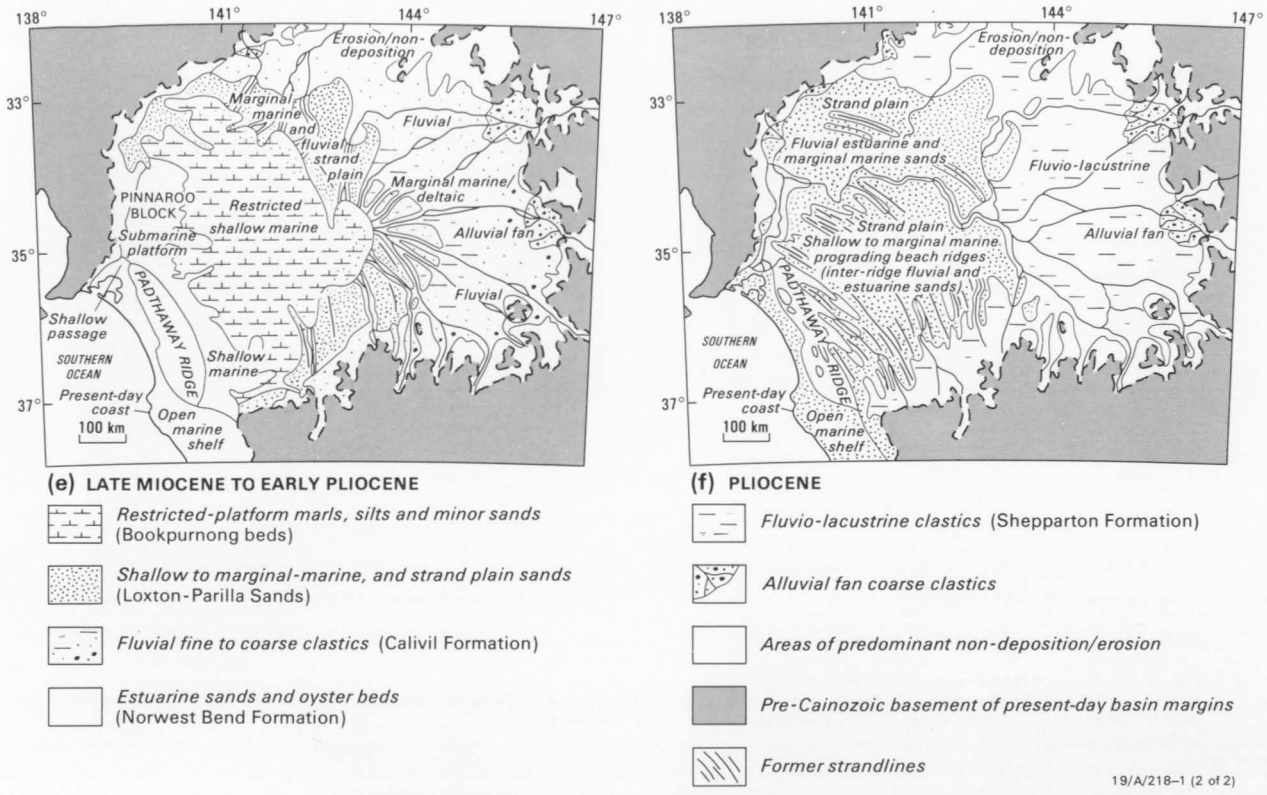


Fig. 168. ctd. – Tertiary palaeogeography.

lacustrine environments, and are characterised by the presence of abundant carbonized and pyritic plant remains, including fossil logs, woody peat, and leaf litter debris. The formation is the thickest and most widely distributed in the Murray Basin, and is only absent over a few concealed basement ridges and beneath the fringes of the basin, where younger sediments onlap rising bedrock topography. Concealed tongues of Olney Formation extend back into the highland zone, where they form part of the sediment infill of tributary valleys. Variations in the thickness of the Renmark Group reflect the unconformable onlap of the unit over irregularities in the pre-Cainozoic surface, as well as subtle and localised synsedimentary basement subsidence (Plate 5). For example, the thick sediments in the depocentre beneath the Riverine Plain are separated from the thick sediments of the central-western depocentre by an arcuate zone of concealed northerly and south-westerly trending basement ridges underlying the southwestern and northwestern borders of the Plain (e.g. Iona Ridge – see Fig. 4; Odins & others, 1985; Kellett, 1989).

Carbonaceous sediments have been recorded in most bores drilled beneath the Riverine Plain, as well as in fault-bounded sub-basins near the basin margins. Coal interbeds range from lignitic brown coal to peat. The peaty coals are thought to have been deposited in extensive paludal swamp and marsh environments; they grade laterally and vertically into carbonaceous clay and sand, of floodplain and meandering channel environments. Other carbonaceous intervals have been logged as wood, presumably from fringing forest environments. Fossil logs and lignitic debris are also common within the fluvial channel sands. At Moorlands in the southwest, the coal interbeds are differentiated as the Moorlands Lignite Member (Ludbrook, 1961a; Harris, 1966). It seems likely that the widespread accumulation and preservation of peat in the Eocene was enhanced during periods of high rainfall, coincident with periods when groundwater tables and sedimentation rates rose as a consequence of rising sea-levels and depositional base-levels. Harris (1985) identified at least four such episodes within the Lower to Upper Eocene sediments of southern Australia, and suggested that many of the Eocene brown coals (those located near the present-day coast) were deposited near shorelines during periods of maximum marine transgression. Peat accumulation is also likely to have been enhanced during periods of warm temperatures, high rainfall, and high fluvial discharge. Oceanic temperatures (Shackleton & Kennett, 1975) and regional palynological studies suggest that Eocene palaeoclimates in southeastern Australia were characterised by warm temperatures

and high rainfall (Kemp, 1978a; Truswell & Harris, 1982; Macphail & Truswell, 1989). Foraminiferal evidence from the adjacent Otway Basin also suggests that marine conditions may have been warm (McGowran, 1978a), or at least temperate with warm intervals (Shafik, 1983).

Tectonic subsidence and high relative sea-levels in the Eocene–Early Oligocene were largely balanced by sediment input, and the Olney Formation is thought to have originated predominantly as fluvio-lacustrine deposits. Micropalaeontological evidence, however, indicates that paralic and minor marine to marginal-marine components are increasingly prevalent within the Upper Eocene sediments towards the top of the Olney Formation in western areas. In the extreme southwest, these are differentiated as the Buccleuch beds (Ludbrook, 1961a) consisting of Upper Eocene to Lower Oligocene shallow-marine glauconitic calcareous clay, thin bryozoan limestone, and minor carbonaceous sand. These are mainly confined to a palaeogeographic feature known as the Buccleuch Embayment (Fig. 55). Other marine/marginal-marine sediments, partly age-equivalent to the Buccleuch beds, but which lack carbonates and are lithologically similar to the Olney Formation (Fig. 55), have been locally identified in western and central-western areas of the basin (Lindsay & Bonnett, 1973; Lindsay, 1985a; Brown & Stephenson, 1986; Macphail, 1988a,b; Macphail & Truswell, 1988, 1989; Lindsay & Barnett, 1989).

In the western Murray Basin, deposition of the Olney Formation was restricted to the Middle Eocene–Early Oligocene, but in the north and east continued until the Middle Miocene (see 'Oligocene–Middle Miocene sequence'). During this extended period of sediment accumulation between 50 and 10 Ma ago, a maximum thickness of only 300 m of sediment was preserved, and deposition was probably intermittent and punctuated by a number of stratal breaks. The most prominent hiatus is thought to have occurred in the late Early Oligocene, accompanying a fall in sea-level (Fig. 167; Brown, 1983, 1985), but the extent and duration of the break may vary across the basin. Ferruginized sediments of the Oligocene Compton Conglomerate and Yanac Member of the Ettrick Formation suggest that at least a partial retreat of the sea from the basin was accompanied by weathering and erosion. In the northeastern Murray Basin, palynological profiles by Martin (1984c) suggest that Oligo-Miocene components may be entrenched up to 50 m within Eocene components (Fig. 53). In addition, Kellett (1988, 1989) has identified at least three subdivisions of the Olney Formation in the Pooncarie–Ivanhoe–Balranald area of the central-northern Murray Basin. Based on palynology, Truswell (1987) and Macphail & Truswell (1989) indicated that most of the upper subdivision lies within the Mid to Late Miocene *Triporopollenites bellus* Zone, the middle unit straddles the Upper *Proteacidites tuberculatus* (Late Oligocene to Early Miocene) and basal *T. bellus* Zones, whereas the lower unit contains pollen assemblages of the Lower to Middle *Nothofagidites asperus* Zones (Middle to Late Eocene) and extends into the Lower *P. tuberculatus* (Early Oligocene) Zone. Martin (1977) indicated that Upper *N. asperus* Zone assemblages have not generally been recognised, although this may be due to a lack of diagnostic palynomorphs, as an equivalent interval has been identified locally (Macphail & Truswell, 1988). Beneath most eastern and northern parts of the Murray Basin, however, Oligocene–Miocene components of the Olney Formation are lithologically indistinguishable from Eocene–Lower Oligocene components, and therefore the variously dated components are regarded as parts of a single lithostratigraphic unit (Brown, 1985).

Oligocene–Middle Miocene sequence

A major marine transgression, about 32 Ma ago (late Early Oligocene) resulted in a dramatic change in sedimentation patterns in the western Murray Basin, and can be correlated with deposition of the marine and marginal-marine formations of the Oligocene to Middle Miocene Murray Group (Fig. 167) over the western Murray Basin. Non-marine sedimentation continued to the east and north (younger components of the Olney Formation – see above), but in western areas the paralic swamp and marsh environments of the Olney Formation were drowned by the marine transgression. In the west, the rates of terrigenous sediment input did not initially balance the combined rates of rise in sea-level and crustal subsidence, and hence the Murray Basin was partly flooded by a shallow epicontinental sea. Rising base-levels resulted in deposition of terrigenous clastics in the east and north, while a diminished terrigenous input to the southwest contributed to the carbonate platform sequence in the southwest. The palaeogeography (Fig. 168c) suggests that a shallow-marine platform in the southwest was flanked to the east and north by a narrow zone of restricted marine and lagoonal en-

vironments. These were in turn bordered by a marginal-marine zone – including extensive distributary bays and tidal flats – further flanked by peat-forming swamps, deltaic, and fluvial environments.

During the initial marine transgression in the late Early Oligocene (Fig. 168c), a thin layer (20–30 m thick) of glauconitic calcareous clay (marl) of the Ettrick Formation (Toe; Ludbrook, 1961a; Lindsay & Williams, 1977) accumulated over patchy, residual, ?sub-aerial quartz-pebble conglomerate and shallow-marine sediments of the Compton Conglomerate in the southwest, and over clastics of the Olney Formation farther north and east. As sea-level continued to rise, the calcareous clay was replaced up-sequence by over 100 m of Upper Oligocene to Middle Miocene shallow-marine limestone (Fig. 168d). This consists of coarse-grained skeletal debris admixed with varying proportions of calcareous clay, micrite and quartz sand. In the west, the limestone is calcarenitic with minor fossiliferous quartz sandstone, but to the east and southeast is increasingly fine-grained, micritic, and has a higher calcareous clay content. The skeletal debris consists of a foramol assemblage of echinoderms, bryozoans, molluscs, and benthic foraminifera (Tml – Murray Group limestones – Gambier, Morgan, Pata, Duddo Limestones, Mannum Formation; Ludbrook, 1961a, 1963; Lindsay & Bonnett, 1973; Lawrence, 1975, Brown, 1985).

To the north and east, the platform limestone grades into a narrow zone of glauconitic calcareous clay and thin limestone of the Winnambool Formation (Tmw – Lawrence, 1975), which is richly fossiliferous and contains well preserved macrofossils – including abundant bryozoans – deposited in the shallow/restricted-marine platform and lagoonal environments (Fig. 168d). The Winnambool Formation is essentially a younger diachronous equivalent of the Ettrick Formation, but whereas the Ettrick Formation pre-dates and underlies the Murray Group limestone, the Winnambool Formation is a lateral facies equivalent of the limestone. The calcareous clay of the Ettrick and Winnambool Formations in turn grades laterally into the Geera Clay (Tmg), consisting of black, locally carbonaceous silt and mud with minor dolomite and sand (Lawrence, 1975; Lawrence & Abele, 1976, 1988), and is characterised by an abundant but much less diverse fauna dominated by gastropods, milliolids, and ostracods. The Geera Clay was deposited in the shallow to marginal-marine environments (Fig. 168c,d) – including extensive interdistributary-bay and tidal-flat environments (Brown, 1985; Truswell & others, 1985). Minor channel sands cut through the predominantly fine-grained unit, which also locally contains evidence of intercalated carbonaceous, freshwater swamp deposits (Truswell & others, 1985; Radke, 1987; Brown & Radke, 1989). To the north and east, the Geera Clay in turn interfingers with deltaic and fluvio-lacustrine silt, sand, clay, and peaty coal of the 'upper' Olney Formation.

Peat accumulation during the Late Oligocene–Middle Miocene was confined to the deltaic and fluvio-lacustrine environments of the eastern and northern parts of the basin (components of Olney Formation of the Renmark Group), and was probably enhanced at sites where rates of groundwater rise, tectonic subsidence and sediment compaction were favourably balanced against rates of sediment input (Brown, 1980; Harris, 1980). When the rise in relative sea-level was rapid, and sediment input remained low, as during the Late Oligocene–Early Miocene marine transgression, then extensive swamp environments were formed and locally drowned. During periods when relative sea-level and the groundwater table fell rapidly, carbonaceous materials were less likely to be preserved.

In the Oligocene–Early Miocene, the dominance of foramol skeletal debris in the limestone of the Murray Group suggests that palaeoclimates, or at least oceanic temperatures, were mainly temperate rather than tropical, although minor extra-tropical incursions of warmer-water forams have also been recorded in southern Australia (McGowran, 1978b). In SADME Oakvale No.1 bore in the northwest of the Murray Basin, palynological evidence from marginal-marine sediments of the Geera Clay suggests that in the Late Oligocene–Early Miocene the regional vegetation was dominated by evergreen rainforest with abundant *Nothofagus brassi*, dependent upon high annual precipitation (Truswell & others, 1985). In the mid-Miocene, nearby open freshwater and swamp conditions are indicated by abundant grass and sedge pollen, in combination with freshwater algae and dinoflagellates, as well as aquatic swamp vegetation characterised by *Sparganium* or *Typha*. Palynological assemblages from younger parts of the Oligo-Miocene sequence in the SADME Oakvale No.1 bore, in the northwest of the basin reveal a change in tree types from species characteristic of evergreen rainforest (growing under year-round precipitation) to types more characteristic of rainforest subject to seasonal variation in rainfall (Truswell & others, 1985; Macphail & Truswell, 1988, 1989). These assemblages are characterised by an increasing

dominance of *Myrtaceae* and abundance of *Araucariceae*. Rainfall was probably higher and less seasonal towards the east, where palynological investigations of boreholes beneath the Riverine Plain indicate that humid conditions prevailed until at least the Middle Miocene (Martin, 1977, 1984a).

As indicated by the distribution of the Geera Clay (Fig. 79; Plate 9), the zone of marginal-marine sedimentation migrated within a relatively narrow 100 km wide zone between the Late Oligocene to Middle Miocene. A number of eustatic events occurred, but no major retreat of the sea from the basin has been identified until the late Middle Miocene. As sea-level began to fall in the mid-Miocene (approximately 10 Ma ago), the Olney Formation, the Geera Clay and the Winnambool Formation appear to have locally prograded back over the top of the platform limestones of the Murray Group, so that deltaic and fluvio-lacustrine sediments of the Olney Formation locally overlie the Geera Clay, which partly envelopes the marls, which in turn partly envelop the limestones. The retreat of the sea was followed by a short period of non-deposition/non-preservation, and a disconformity has been recognised separating the sediments of the Oligo-Miocene sequence from those of the Upper Miocene – Pliocene sequence. The extent and duration of the retreat of the sea are uncertain. Most authors have suggested that the sea entirely retreated from the basin, whereas in contrast Carter (1985), whilst recognising the presence of a disconformity, proposed that non-deposition occurred as a consequence of rising sea-level and increased water depth rather than retreat of the sea. To the east, however, the major fall in sea-level in the Late Miocene can be correlated with development of the Mologa Surface, a land surface associated with weathering and erosion in the basin, and with active entrenchment of adjacent highland valleys (Macumber, 1978b).

Upper Miocene – Pliocene sequence

Deposition of the last major Tertiary sequence of the basin can in turn be correlated with commencement of a further short-lived marine transgression – regression in the Late Miocene – Pliocene (Fig. 168e; Brown, 1983, 1985; Carter, 1985). An initial rise in sea-level resulted in the marine clay and marl of the Bookpurnong beds (Tpb). These are glauconitic, locally highly fossiliferous, and accumulated in shallow-marine environments. They are, however, absent over much of the Pinnaroo Block in the southwest, and were either eroded from the block prior to deposition of the Loxton – Parilla Sands in that area, or alternatively, onlapped the block from the northeast (see distribution of Bookpurnong beds, Fig. 84). Palaeogeographic reconstructions (Fig. 168e) suggest that the block was eroded in the early Late Miocene, but in the late Late Miocene it may have formed a submarine barrier between the Murray Basin and the open ocean. Uplift of the block, to the southwest of the Murrayville Fault, in the Late Miocene may have resulted in the trapping of sediment within the areas of relative subsidence to the northeast of the block. Carter (1985, his p.19) reported that in cliffs of the Murray River, 14 km west-northwest of Loxton, Bookpurnong beds overlie an eroded, ferruginised and barnacle-encrusted surface of Miocene limestone, but suggested that erosion may have occurred in deeper-water rather than shallow-marine or subaerial settings.

To the east and north, the Bookpurnong beds are flanked by shallow to marginal-marine sands of the basal Loxton – Parilla Sands (Tps). Farther inland, these are in turn flanked by coarse-grained quartzose sand and gravel of the fluvial and fluvio-lacustrine Calivil Formation (Tpc; Lawrence & Abele, 1976, 1988; Macumber, 1978a,b), which forms an extensive sand sheet underlying much of the eastern and northern margins of the Murray Basin. As a consequence of rising base levels (rising sea-level in the Late Miocene – Early Pliocene), and diminished potential for erosion, the locus of deposition appears to have extended up the entrenchments within the previously incised palaeovalleys (incised during the late Middle Miocene to early Late Miocene marine regression – see above), which were then backfilled to form the youngest of several Tertiary 'deep-lead' systems of northern Victoria (Hunter, 1909; Macumber, 1978b). Towards the basin margins, the formation consists mainly of quartz and kaolin, thought to be erosional products derived from the Mologa surface. The formation is increasingly fine-grained downbasin, where it interfingers with the base of the overlying finer-grained Shepparton Formation. Beneath the western Riverine Plain, Calivil Formation equivalents include both marine fossils and carbonaceous intercalations (i.e. 'Bookpurnong Beds equivalents' of Ludbrook, 1962a), and are thought to have been formed in a fluvio-deltaic/marginal-marine environment (Fig. 168e), located approximately beneath the western apex of the present-day Riverine Plain, and transitional between the fluvial environments to the east and marine to the west.

Palaeogeographic reconstructions of the subsequent period of marine regression, in the Early Pliocene (approximately 4–2 Ma ago), suggest that a floodplain in the east and north was flanked to the west and south by an extensive sand sheet (Fig. 168f). In the west, the floodplain was connected to the Southern Ocean by a zone of fluvial and estuarine environments that roughly coincided with the present-day course of the Murray River. As the regression proceeded, the upper surface of the sand sheet formed a composite strandplain (Brown, 1983, 1985) of stranded shallow-marine and beach-ridge sands, as well as of younger, inter-ridge, and locally cross-cutting (partly disconformably entrenched) fluvial and estuarine, quartz sand deposits of the Loxton–Parilla Sands (Fig. 90; Tps – Ludbrook, 1961a; Firman, 1973; Lawrence, 1975; Macumber, 1978a,b). These now form an extensive, deflated, near-surface sand sheet, underlying the Quaternary Blanchetown Clay and aeolian dunefields of the western Murray Basin. Stranded shallow-marine and beach ridges and associated swales form prominent surface features over much of the strandplain in western Victoria and adjacent areas of South Australia, whereas several generations of estuarine and fluvial deposits dominate the succession along, and to the north of, the Murray River (Fig. 168f). Some of the estuarine and fluvial components have been defined as separate units where exposed by the Murray River (see 'Loxton–Parilla Sands'). Firman (1966c, 1971b, 1972, 1973), for example, described the estuarine Lower Loxton Sands, fluvial Upper Loxton Sands, fluvial Pliocene Parilla Sand (as originally defined in S.A., – not as applied in Vic.) and Pleistocene Chowilla Sand, while Gill (1973a) differentiated the Late Pliocene to ?Early Pleistocene Moorna Formation. Beyond the type areas exposed by the Murray River, however, the stratigraphic relationships and distributions of these sandy fluvial units are poorly known, and although equivalents undoubtedly exist elsewhere in the western Murray Basin, the various shallow-marine, marginal-marine and fluvial components cannot readily be distinguished within the Loxton–Parilla Sands.

At the western margin of the basin, estuarine oyster beds of the Upper Pliocene Norwest Bend Formation (Fig. 100; Tpn – Ludbrook, 1961a) were deposited during a minor subsequent high stand of sea-level and delineate the location of a Pliocene ancestor of the Murray River, roughly coincident with the present-day river (Twidale & others, 1978).

In the east and north, the major regression in the Pliocene can be correlated with deposition of the fine-grained clastics and polymictic sand and gravel of the Shepparton Formation (TQs; Lawrence, 1966, 1975) by aggradation in the flood-plain environment.

Palaeoclimates during the late Cainozoic are thought to have been characterised by increasing seasonal aridity (Bowler, 1982; Macphail & Truswell, 1989). A late Pliocene period of non-deposition is indicated by the presence of the ferruginised and silicified lateritic Karoonda Surface, which weathered the upper surface of the Loxton–Parilla Sands prior to commencement of deposition of the predominantly Pleistocene Blanchetown Clay in the latest Pliocene. The presence of this lateritic surface suggests that seasonally humid climates prevailed until at least the Late Pliocene, and contrasts with the calcareous calcretes and pedogenic surfaces, which are characteristic of the Late Quaternary arid to semi-arid landforms of the Murray Basin (Bowler, 1982).

Quaternary sedimentation

The Quaternary sediments of the Murray Basin were deposited in a variety of geologic environments, including aeolian, fluvial, lacustrine, coastal, shallow marine, colluvial, and pedogenic. The Quaternary sedimentary record is the product of interactions between topography, tectonics, climatic fluctuations, vegetation, groundwater levels, and base level changes (of both sea-level and internal drainages, such as Lake Bungunnia). Late Quaternary sedimentation styles and processes have been particularly sensitive to subtle palaeoclimatic and palaeohydrologic fluctuations.

Early Pleistocene. In the southwestern Murray Basin, uplift of the Pinnaroo Block about 2.5 Ma ago led to the damming of the proto-Murray River near where today's town of Mannum now stands (Figs 119, 169). This in turn led to the formation of Lake Bungunnia, which covered a maximum area of some 33 000 km^2 and persisted as a contiguous megalake until about 0.7 Ma. The lacustrine Blanchetown Clay (Qpc) and intercalated fluvial sediments were deposited in and on the flanks of Lake Bungunnia throughout this time. Lake Bungunnia was shallow (less than 80 m at its deepest, and averaging perhaps 30 m), and did not have a permanent outlet stream for much of its existence. Stephenson (1986) showed that Lake Bungunnia existed under conditions at least twice as wet as those of the Holocene, and that minor fluctuations in climate caused major lake shore migrations. In the

interval between about 0.9–0.8 Ma, the thin Bungunnia Limestone was deposited in western parts of Lake Bungunnia.

Lake Bungunnia dominated the western Murray Basin in the latest Pliocene to Early Pleistocene, but to the northwest was flanked by the colluvial Pooraka Formation (Qfr), which was deposited throughout the Quaternary (mainly in the Early Pleistocene). At the northwest margin of the basin, the Pooraka Formation was deposited as a consequence of Late Pliocene–Quaternary uplift of the flanking ranges. In the east and north of the basin, fluvial sedimentation of the Shepparton Formation (TQs) continued, resulting in formation of the modern Riverine Plain (see Figs 14, 107). This remains an important physiographic entity today.

In the Eastern Highlands and associated highland valleys, as well as in parts of the Gambier and Buccleuch Embayments, widespread accumulation of basaltic lava, agglomerate, scoria, tuff, and related volcaniclastic sediments (TQv) took place. These "Newer Volcanics" are of predominantly Late Tertiary age in western Victoria, but are progressively younger to the west, with Mount Gambier having been active 4500 yrs ago, and Mt Schank as recently as 1500 yrs (Firman, 1973).

In coastal areas to the southwest of the basin, the Early Pleistocene was a time of marine transgression, when the Buccleuch Embayment of the Murray Basin and Gambier Embayment of the Otway Basin were geologically more closely related to each other than to other parts of their respective basins. The Oligo-Miocene Gambier Limestone and the Miocene Mannum Formation and Morgan Limestone were extensively eroded and reworked during the transgression, and the sandy limestone of the Coomandook Formation (Qpl) formed from the debris, particularly in the Buccleuch Embayment and northern Gambier Embayment.

Late Pleistocene–Holocene. The sea regressed slowly from coastal areas of the Buccleuch and Gambier Embayments throughout the Late Pleistocene, when the coastal plain was being gently uplifted (Cook & others, 1977). During this period, a number of minor eustatic fluctuations resulted in a series of stranded coastal ridges (calcarenites of the Bridgewater Formation, Qpb – Cook & others, 1977). It is uncertain whether the sea entirely retreated from the Buccleuch Embayment after the Early Pleistocene Coomandook Formation, but a period of non-deposition occurred prior to the oldest dunes of the Bridgewater Formation, and oldest back-barrier unnamed lagoonal sediments (dolomites

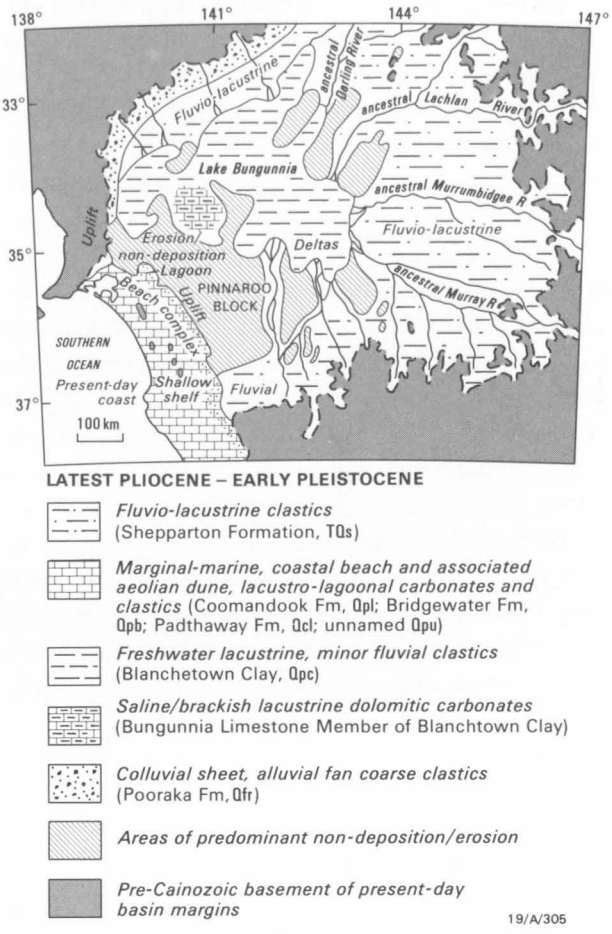


Fig. 169. Latest Pliocene to Early Pleistocene (2.5–0.7 Ma) palaeogeography of the Murray Basin.

of Qpu; Rogers, 1980a), which may have commenced between 0.9–0.8 Ma. A series of up to twenty coastal ridges of Bridgewater Formation of Late Pleistocene age (some representing multiple eustatic high-stands – Cook & others, 1977), were subsequently stranded on a gently uplifting coastal plain (Fig. 128). Lagoonal, lacustrine, peat swamp, and fluvial sediments of the Padthaway Formation (Qcl) accumulated between the stranded ridges. The same processes still operate today: the Holocene coastal dune complex is known as the Semaphore Sand (Qhe), whilst back-barrier dolomites are currently forming in the restricted Coorong Lagoon (Qhl). In the early Holocene, high water levels in the Murray River estuary led to deposition of the lacustrine St. Kilda Formation (Qho).

In the western Murray Basin, significant changes in sedimentation patterns took place following the demise of Lake Bungunnia commencing at about 0.7 or 0.6 Ma, and accompanying the onset of modern semi-arid climatic conditions at about 0.4 Ma (An Zhi–Sheng & others, 1986). For most of its exist-

ence, Lake Bungunnia did not have a permanent outlet stream, but when one developed at about 0.7 Ma, the water level in the lake rapidly dropped, fragmenting Lake Bungunnia into several smaller lake basins (Stephenson, 1986). Most of these lakes disappeared as the climate deteriorated, but some stabilized within low-lying areas of groundwater discharge (Fig. 143), within which gypsiferous sediments (Qly – Yamba Formation) were deposited. Lake Tyrrell is the largest of these surviving remnants of Lake Bungunnia. Fluvial processes continued in the western Murray Basin during the period 0.7 Ma to 0.4 Ma, but, with the exception of Shepparton Formation equivalents along the course of the Murray River, little evidence of this has been preserved. This is presumably because the demise of Lake Bungunnia caused a substantial lowering of baselevel, leading to reworking of older sediments, such as the upper parts of the Blanchetown Clay (Stephenson, 1986), which shows evidence of an uneven, channelled, upper surface (Rogers, 1978).

Climatic deterioration in the western Murray Basin was gradual, and it was not until approximately 0.5–0.4 Ma that true arid to semi-arid conditions prevailed (Bowler, 1982). Saline groundwaters have accumulated within the near-surface Pliocene Sands aquifer system during the Late Pleistocene, and development of many of the distinctive landforms of the Murray Basin can be related to climatic variation, and the interactions between fluctuating saline groundwater tables and surface geomorphic processes. Aeolian dunefields, groundwater discharge lakes and associated gypsum and clay pellet lunettes, bedload channel sands ('prior streams'), and associated source-bordering dunes, were all activated during onset of glacial aridity. During slightly more pluvial inter-glacial periods, the aeolian landforms were stabilised by vegetation, river channels carried a suspended-load, and sand-dominated lunettes formed by deflation of beach sands from freshwater lakes.

In the western Murray Basin, the aeolian sediments include the 'Qdp' unnamed sand plains, located between colluvial deposits (Qfr) of the northern ranges and Woorinen Formation dunefields (Fig. 130; Brown & Stephenson, 1985). These sand plains are believed to have a predominantly aeolian origin, but towards the northwestern basin margin they merge with material partly formed by colluvial outwash processes.

The Woorinen Formation (Qdw) constitutes the oldest dunefields. It is the most extensive surface unit in the western part of the basin, and began to accumulate by at least 0.4 Ma. It is typified by west–east trending longitudinal dunes, most of which are currently stabilised by vegetation and pedogenic processes. These dunes were remobilised during a number of past periods of aridity, reflecting Late Quaternary oscillations between arid and semi-arid climatic conditions. Several such phases of remobilisation are recorded by the presence of calcareous palaeosols and calcrete horizons (see 'Woorinen Formation'; Fig. 134 and Table 35). Calcretes (Qca) can form by several mechanisms, in pedogenic, groundwater, lacustrine, and biogenic environments, and in the Murray Basin developed throughout much of the Late Pleistocene. A large number of pedogenic calcretes are known from within dunes of the Woorinen Formation, but at least three Late Pleistocene periods when calcrete genesis was particularly extensive have been identified in the western Murray Basin (Firman, 1963, 1966e, 1973). The oldest of these named calcretes is the massive, sheet-like Ripon Calcrete, which is thought to have been precipitated some 0.6 Ma to 0.5 Ma ago. The other 'stratigraphic' calcretes are the Bakara Calcrete, which is thought to be 0.5 Ma to 0.4 Ma old, and the less readily dated Loveday Soil, which is less than 0.4 Ma but more than 0.01 Ma old, with an age nearer the upper limit being more probable.The Quaternary was not a time of great tectonic activity in the Murray Basin, even though the western margins of the basin underwent significant uplift in the Pliocene–Pleistocene. A notable exception is the Morgan fault near the western margin of the basin, which developed a throw of 150 m (S.R. Barnett, pers. comm., 1984).

As noted above, the initiation and re-activation of the aeolian landforms of the basin (Figs 14, 130) have been climatically controlled, but the distribution of dunefields relative to fluvial plains reflects the availability of sand from the underlying Pliocene strandplain of Loxton–Parilla Sands. Rainfall and evaporation contours are aligned roughly east–west, rather than north–south (see Fig. 10). A comparison of the distributions of the Pliocene Loxton–Parilla Sands and of the Shepparton Formation, relative to the distribution of the dunefields indicates that, given an appropriate climate, the sand availability has been the major controlling factor on dunefield development. In western areas of the basin, arcuate northwesterly trending ridges and swales of Pliocene sand, with a subdued topographic expression, have been deflated by winds blowing from the west to west-southwest, to form the Quaternary dunefields. The high clay content within the Woorinen Forma-

tion dunes was probably derived from the underlying Blanchetown Clay and younger saline lakes (see 'Woorinen Formation'). In contrast, the sand and loess plains to the northeast and southeast (Fig. 14) lack dunes and in most places overlie fine clastics of the Shepparton Formation. Wind-blown clay-size sediment ('parna' of Butler, 1956) occurs over much of the Riverine Plain in the east, but dunefields are small and are restricted largely to reworked fluvial channel sands. A number of small dunefields occur at the eastern margins of the basin where sand has been dropped by westerly winds rising to cross the adjacent eastern highlands. The sands of the Pliocene strandplain have thus been extensively eroded and reworked during Late Pleistocene in-situ aeolian deflation to form the Quaternary Woorinen Formation of the Mallee landscape. In the southwest, many of the regressive ridges have now been entirely eroded, but resistant Quaternary calcretes which developed within the ridges or in the intervening swales now define former ridge trends (Qca).

Parts of the Woorinen Formation were remobilised and reworked as the 'Qdu' dunefields of Brown & Stephenson (1985), which consist of irregular to subparabolic mobile dunes in western New South Wales. This remobilisation is thought to have occurred during the latest Pleistocene, at the same time as the Molineaux–Lowan Sands (Qmd) dunefields were accumulating farther south in South Australia and western Victoria. The Molineaux–Lowan Sands form extensive tongue-shaped dunefields with the appearance of mega-blowouts (Little, Big, and Sunset Deserts), and developed by the deflation the Loxton–Parilla Sands, the Bridgewater Formation, and the Woorinen Formation. The Molineaux–Lowan Sands are highly mobile, and as a consequence of vegetation clearance, over-grazing and bush fires these dunes are locally active today.

At times in the Late Pleistocene, previously perennial lakes in the central and western Murray Basin became intermittent. Lunettes (Qdl) were constructed on their eastern shores owing to the action of the predominant westerly winds (Fig. 143). Some of these lunettes are composed of layers of predominant clay pellets alternating with layers of predominant quartz sand, whereas others are almost entirely composed of clay, sand or gypsum. In general, clay pellet components were deposited by deflation of saline lake floors during the transition between wet and dry periods, whereas sand dominated components were deposited by deflation of lake shore beaches during wetter lake-full periods (Bowler & Wasson, 1984; see 'Interpretation of Environment of Deposition' of Qdl). The best-known lunettes in the Murray Basin are those associated with the Willandra Lakes system in western New South Wales, where at least three separate periods of lunette accretion, between about 120 000 and 15 000 yrs. ago are preserved (Bowler, 1980). Most of the lunettes of the basin are fossil features and are currently subject to deflation, leaving mobile dunes of residual white sand in the crestal areas of some mixed-layer lunettes. At present, the processes which resulted in the construction of the lunettes can be seen to operate intermittently at some sites, such as Lake Tyrrell (Teller & others, 1982; Bowler & Teller, 1986). The location of many surface groundwater discharge sites can be related to groundwater outcrop within low-lying areas of subsidence. In many cases they can also be related to flow disruption at permeability barriers developed where underlying aquifers, and the Renmark Group aquifer system in particular, are truncated stratigraphically or are significantly thinned by concealed basement barriers.

As the Mallee region in the west was coming under semi-arid climatic conditions at about 0.5–0.4 Ma, the Shepparton Formation continued to be deposited in the Riverine Plain in the east (Fig. 107). As described elsewhere (see 'Shepparton Formation' and 'Coonambidgal Formation'), variations in fossil channel types at the surface of the Riverine Plain have also been influenced by fluctuations in Quaternary palaeoclimate. The very large wave-length (relatively straight), bed-load 'prior stream' channels are thought to have formed during periods of glacial aridity, when springtime meltwaters resulted in high seasonal discharge. A lack of vegetation cover, both within the basin and over the adjacent highlands, contributed to high sediment input. In contrast, the 'ancestral stream' meander channels are characterised by large wave-length, but significantly higher amplitude, and contained, at least seasonally, a higher discharge than their modern counterparts. They carried a greater suspended load, than 'prior' channels, indicating a return of vegetation to the adjacent highlands (Bowler, 1978a). Source-bordering dunes ('Qad' of Brown & Stephenson, 1985) were formed adjacent to streams, by aeolian reworking of point-bar and other fluvial sand deposits during periods of glacial aridity. Most are stabilised by vegetation, but some are currently being eroded by deflation. The Bunyip Sand was deposited in source-bordering dunefields during the last 7000 yrs. from sand blown out of the Murray River Gorge. The

name Coonambidgal Formation (Qa) is given to the sediments of modern rivers and intermittent streams, deposited in flat, low-lying, generally narrow, meander belts, anastomosed distributaries, and confined flood plains. Coonambidgal Formation occurs in widely distributed active and recently active channels incised within older fluvial sediments of the Riverine Plain and adjacent tributary highland valleys. In the west, it is confined to the floodplains of the Murray and Darling Rivers, to areas of internal drainage within the aeolian landscape, and to local alluvial deposits in the valleys of the intermittent modern creeks of the Mount Lofty and Flinders Ranges.

The Murray River Gorge was cut into up-faulted Miocene limestones of the Pinnaroo Block during several Late Quaternary low stands of sea level (Twidale & others, 1978). Those workers, however, suggested that the initial gorge was cut before Lake Bungunnia developed, but this is thought to be unlikely, given the time of origin of that lake at about 2.5 Ma (Stephenson, 1986). It is more probable that the present Murray River gorge dates from the demise of Lake Bungunnia around 0.7–0.6 Ma. It was successively excavated and deepened during times of glacio-eustatic low baselevel in the Late Pleistocene, and back-filled with sediment during inter-glacial periods of high baselevel.

Fig. 170. Surface discharge of saline groundwater in Manangatang region of northern SWAN HILL.

ECONOMIC GEOLOGY

Groundwater is currently the most important geologic resource of the Murray Basin, but others include Cainozoic alluvial gold, gypsum, halite, limestone, and kaolin. Heavy mineral suites, identified in near-surface Pliocene Loxton–Parilla Sands, are under investigation, and a large deposit has been discovered in the Horsham region. The Cainozoic succession also includes extensive deposits of Tertiary brown coal, and is underlain by Upper Permian coal measures in the Oaklands Basin. The Cainozoic sediments are not prospective for hydrocarbons, but several of the concealed pre-Cainozoic infrabasins have not yet been fully investigated. Mineral occurrences are listed on Table 44; localities are shown on Figure 171. Reports on mineral and petroleum exploration activity are held in open-file archives in each of the various State Mines Departments and Geological Surveys.

Groundwater

Groundwater forms the basis for the economic viability of many sheep and cattle stations, and is also extensively used for irrigation and town water supplies. Surface waters from the Murray River and its tributaries are also used for irrigation schemes as well as for town water supplies. In addition, Adelaide, Whyalla and other South Australian urban centres outside the basin are dependent on water pumped from the Murray River. The clearance of natural vegetation and the development of irrigation schemes have, however, resulted in increased infiltration from the surface to the aquifer systems. This, in turn, has resulted in rising groundwater levels accompanied by the discharge of saline groundwaters to the landscapes and river systems of the basin, creating salinity problems that threaten to have an increasingly adverse impact on both the regional economy and natural environment (see Chapter 1 – 'Background to Murray Basin Hydrogeological Project'). Groundwater investigations have therefore been concerned partly with the management of the groundwater resource, partly with the management of irrigation and dryland salinity problems, and partly with the maintenance of water quality in the Murray River and its tributaries. The exact number of bores which exploit the groundwater resources of the basin is not known (many old or shallow bores are not licensed), but records of at least 30 000 are available from the South Australian part of the basin, which has the greatest density of boreholes. Coastal areas in the southwest of the Murray Basin are partly separated from the main Murray groundwater basin by a groundwater divide, and are not discussed in

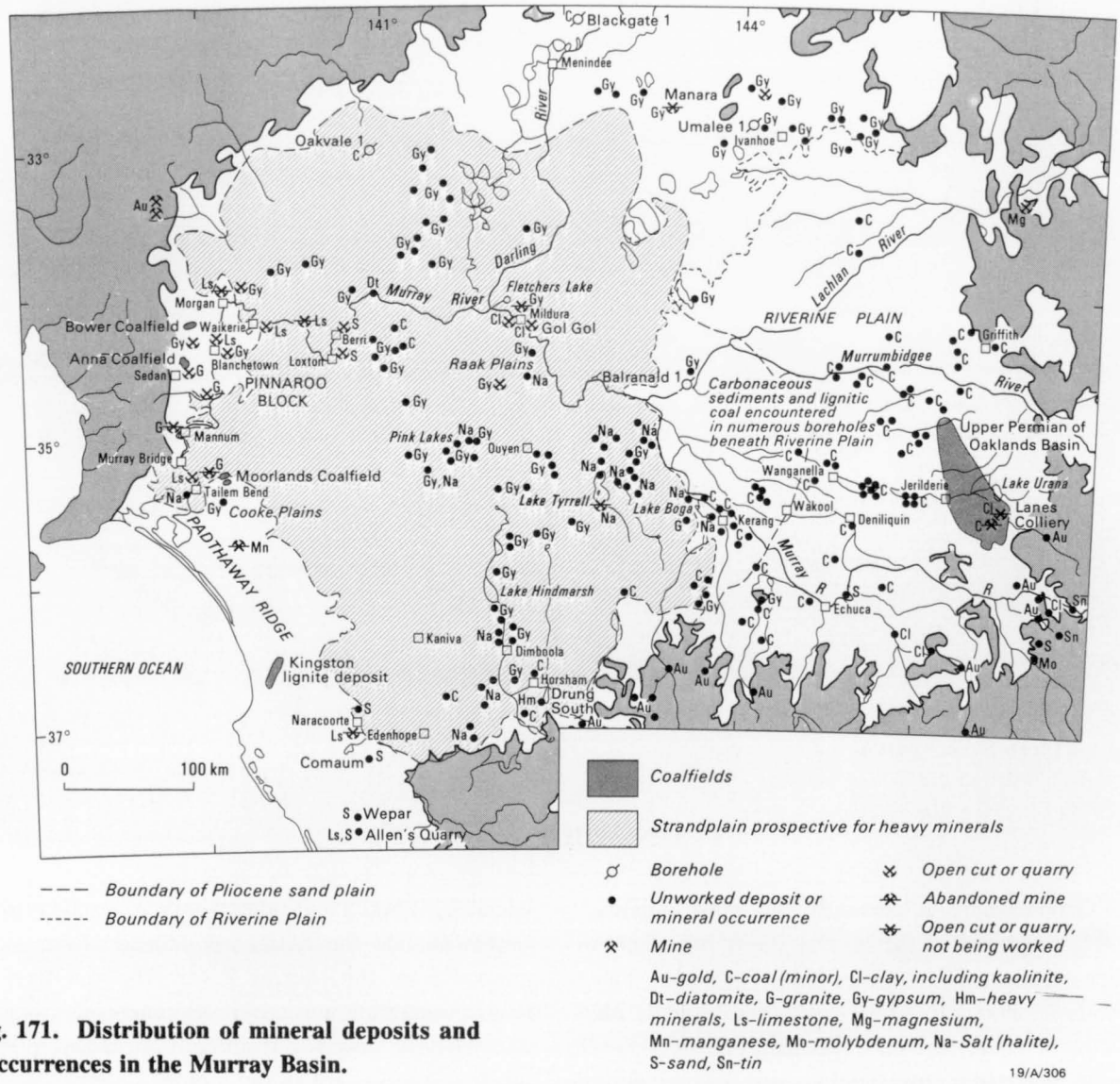


Fig. 171. Distribution of mineral deposits and occurrences in the Murray Basin.

detail below. Various aspects of the hydrogeology of southwestern areas are described by O'Driscoll (1960), Waterhouse (1977), Waterhouse & Gerges (1979), Williams (1979), Wing (1982), Stadter (1984), Stadter & Love (1987, 1989), and Love & Stadter (1988). The hydrogeology of the Cainozoic sediments of the Hindmarsh Tiers and Myponga Basins in the adjacent Mt. Lofty Ranges has been described by Furness & others (1981).

Regional aquifer/aquitard systems of the Murray Basin

Pre-Cainozoic. An Upper Cretaceous weathering surface forms an impermeable seal over much of the pre-Cainozoic basement at the base of the Murray Basin, and the known groundwater resources are almost entirely confined to the Cainozoic succession. However, at the margins of the basin, a number of bores obtain supplies from shallow fractured rock aquifers in the basement (e.g. western margin – Barnett, 1980, 1981a,b). Little is known of the aquifer characteristics of the underlying pre-Cainozoic sedimentary rocks, although Reed (1980) noted that Devonian sandstones in A.O.G Tararra No.1 (Tararra Trough) have porosities averaging 13.4%, with a maximum of 20.8% (Boyd & Heisler, 1967). The Lower Permian mainly forms a confining bed, although argillaceous sand intervals with relatively good permeabilities are known (e.g. basal sand in Monash No.1; Walter, 1965). In the east, a number of aquifers within the Upper Permian and Triassic sediments of the Oaklands Basin are currently being examined as part of an investigation into the feasibility of resuming coal mining from the Upper Permian Coorabin Coal Measures.

Quartzose basal Cretaceous sands (Pyap Member of Monash Formation; see Table 7) in bores drilled into the Renmark Trough are relatively clean with porosities ranging from 26% to 41% (Der-

TABLE 44. OCCURRENCES OF MINERAL RESOURCES (page 1 of 3)

Commodity	*Latitude*	*Longitude*	*Map Sheet*	*Remarks*
Clay	34 11 S	142 05 E	MILDURA	Open cut quarry
Clay	34 11 S	142 11 E	MILDURA	Open cut quarry
Clay	36 19 S	145 21 E	BENDIGO	Occurrence
Clay	35 28 S	146 12 E	JERILDERIE	Oaklands kaolin clay mine – abandoned
Clay	36 08 S	146 41 E	WANGARATTA	Occurrence
Clay	36 25 S	145 41 E	WANGARATTA	Kaolinite occurrence
Coal	34 11 S	139 24 E	ADELAIDE	Bower Coalfield
Coal	34 27 S	139 20 E	ADELAIDE	Anna Coalfield
Coal	35 12 S	139 39 E	PINNAROO	Moorlands Coalfield
Coal	36 33 S	140 03 E	NARACOORTE	Kingston Lignite deposit
Coal	34 17 S	141 07 E	MILDURA	Occurrence in Sunset 1
Coal	36 54 S	142 11 E	HORSHAM	Occurrence in borehole
Coal	35 24 S	143 42 E	SWAN HILL	Occurrence in borehole
Coal	35 31 S	143 56 E	SWAN HILL	Occurrence in borehole
Coal	35 36 S	143 58 E	SWAN HILL	Occurrence in borehole
Coal	34 16 S	145 14 E	HAY	Occurrence in borehole
Coal	34 29 S	145 13 E	HAY	Occurrence in borehole
Coal	34 33 S	145 02 E	HAY	Occurrence in borehole
Coal	34 37 S	145 25 E	HAY	Occurrence in borehole
Coal	34 50 S	145 17 E	HAY	Occurrence in borehole
Coal	35 08 S	144 45 E	DENILIQUIN	Occurrence in borehole
Coal	35 15 S	145 04 E	DENILIQUIN	Occurrence in borehole
Coal	36 10 S	144 11 E	BENDIGO	Occurrence in borehole
Coal	34 12 S	145 56 E	NARRANDERA	Occurrence in borehole
Coal	34 18 S	146 08 E	NARRANDERA	Occurrence in borehole
Coal	34 42 S	145 38 E	NARRANDERA	Occurrence in borehole
Coal	34 56 S	145 34 E	NARRANDERA	Occurrence in borehole
Coal	35 30 S	146 08 E	JERILDERIE	Lambs Colliery – abandoned; part of Oaklands Basin (Upper Permian) beneath the Murray Basin.
Diatomite	34 00 S	140 56 E	CHOWILLA	Occurrence
Diatomite	35 19 S	140 13 E	PINNARRO	Occurrence
Gold	36 59 S	142 41 E	ST ARNAUD	Alluvial, deep lead systems (outside Murray Basin)
Gold	36 35 S	143 26 E	ST ARNAUD	Alluvial, deep lead systems (outside Murray Basin)
Gold	36 36 S	143 44 E	ST ARNAUD	Alluvial, deep lead systems (outside Murray Basin)
Gold	36 44 S	143 17 E	ST ARNAUD	Alluvial, deep lead systems (outside Murray Basin)
Gold	36 48 S	143 08 E	ST ARNAUD	Alluvial, deep lead systems (outside Murray Basin)
Gold	36 55 S	143 19 E	ST ARNAUD	Alluvial, deep lead systems (outside Murray Basin)
Gold	36 48 S	144 06 E	BENDIGO	Alluvial occurrence
Gold	35 37 S	146 39 E	JERILDERIE	Residual or colluvial occurrence
Gold	35 57 S	146 24 E	JERILDERIE	Alluvial occurrence
Gold	36 01 S	146 35 E	WANGARATTA	Alluvial occurrence
Gold	36 07 S	146 29 E	WANGARATTA	Alluvial occurrence
Gold	36 09 S	146 35 E	WANGARATTA	Alluvial occurrence
Gold	36 31 S	145 57 E	WANGARATTA	Alluvial occurrence
Gold	36 58 S	145 59 E	WANGARATTA	Alluvial occurrence
Gold	33 20 S	139 09 E	BURRA	Mine
Gold	33 24 S	139 09 E	BURRA	Mine
Granite	34 31 S	139 21 E	ADELAIDE	Quarry
Granite	34 55 S	139 15 E	ADELAIDE	Abandoned quarry
Granite	34 40 S	139 31 E	RENMARK	Quarry
Granite	35 12 S	139 30 E	PINNAROO	Abandoned quarry
Gypsum	34 19 S	139 22 E	ADELAIDE	Craigie Plains deposit – open cut mine
Gypsum	33 56 S	139 48 E	CHOWILLA	Morgan deposit – open cut mine
Gypsum	33 47 S	140 22 E	CHOWILLA	Parcoola deposit
Gypsum	33 58 S	140 45 E	CHOWILLA	Rotten Lake deposit
Gypsum	33 51 S	140 05 E	CHOWILLA	Occurrence
Gypsum	34 23 S	139 41 E	RENMARK	Blanchetown – open cut mine
Gypsum	34 18 S	140 55 E	RENMARK	Occurrence
Gypsum	34 26 S	140 56 E	RENMARK	Occurrence
Gypsum	35 25 S	139 38 E	PINNAROO	Occurrence
Gypsum	33 00 S	141 26 E	ANABRANCH	White Lake – occurrence
Gypsum	33 07 S	141 21 E	ANABRANCH	Salt lake – occurrence
Gypsum	33 15 S	141 17 E	ANABRANCH	Occurrence
Gypsum	33 14 S	141 28 E	ANABRANCH	Kopi Plain – occurrence
Gypsum	33 14 S	141 31 E	ANABRANCH	Occurrence
Gypsum	33 20 S	141 34 E	ANABRANCH	Occurrence
Gypsum	33 28 S	141 33 E	ANABRANCH	Occurrence
Gypsum	33 29 S	141 29 E	ANABRANCH	Occurrence

TABLE 44. ctd. (page 2 of 3)

Commodity	*Latitude*	*Longitude*	*Map Sheet*	*Remarks*
Gypsum	33 28 S	141 24 E	ANABRANCH	Occurrence
Gypsum	33 31 S	141 22 E	ANABRANCH	Occurrence
Gypsum	33 35 S	141 19 E	ANABRANCH	Occurrence
Gypsum	33 36 S	141 16 E	ANABRANCH	Occurrence
Gypsum	33 39 S	141 20 E	ANABRANCH	Occurrence
Gypsum	33 39 S	141 12 E	ANABRANCH	Occurrence
Gypsum	33 44 S	141 10 E	ANABRANCH	Occurrence
Gypsum	33 39 S	141 15 E	ANABRANCH	Occurrence
Gypsum	33 42 S	141 18 E	ANABRANCH	Occurrence
Gypsum	33 44 S	141 25 E	ANABRANCH	Occurrence
Gypsum	33 32 S	142 13 E	ANABRANCH	Hells Hole Swamp occurrence
Gypsum	33 34 S	142 12 E	ANABRANCH	Salt lakes – occurrence
Gypsum	34 38 S	141 58 E	MILDURA	Raak Plain open cut mine & occurrence
Gypsum	34 23 S	141 05 E	MILDURA	Occurrence
Gypsum	34 30 S	141 00 E	MILDURA	Occurrence
Gypsum	34 45 S	141 08 E	MILDURA	Occurrence
Gypsum	34 24 S	142 14 E	MILDURA	Occurrence
Gypsum	34 28 S	142 14 E	MILDURA	Occurrence
Gypsum	35 03 S	141 37 E	OUYEN	Occurrence
Gypsum	35 02 S	141 46 E	OUYEN	Occurrence
Gypsum	35 05 S	141 32 E	OUYEN	Occurrence
Gypsum	35 09 S	141 33 E	OUYEN	Occurrence
Gypsum	35 07 S	141 12 E	OUYEN	Occurrence
Gypsum	35 13 S	141 23 E	OUYEN	Occurrence
Gypsum	35 08 S	141 46 E	OUYEN	Occurrence
Gypsum	35 21 S	141 56 E	OUYEN	Occurrence
Gypsum	35 55 S	141 56 E	OUYEN	Occurrence
Gypsum	35 06 S	142 15 E	OUYEN	Occurrence
Gypsum	35 07 S	142 17 E	OUYEN	Occurrence
Gypsum	35 08 S	142 20 E	OUYEN	Occurrence
Gypsum	35 11 S	142 24 E	OUYEN	Occurrence
Gypsum	35 15 S	142 25 E	OUYEN	Occurrence
Gypsum	35 20 S	142 12 E	OUYEN	Occurrence
Gypsum	35 40 S	142 17 E	OUYEN	Occurrence
Gypsum	35 41 S	142 03 E	OUYEN	Occurrence
Gypsum	35 45 S	142 03 E	OUYEN	Occurrence
Gypsum	36 10 S	141 55 E	HORSHAM	Occurrence
Gypsum	36 14 S	146 56 E	HORSHAM	Occurrence
Gypsum	36 16 S	141 55 E	HORSHAM	Occurrence
Gypsum	36 17 S	142 04 E	HORSHAM	Occurrence
Gypsum	36 20 S	142 03 E	HORSHAM	Occurrence
Gypsum	36 24 S	142 02 E	HORSHAM	Occurrence
Gypsum	36 40 S	142 05 E	HORSHAM	Occurrence
Gypsum	32 36 S	142 50 E	MANARA	Occurrence
Gypsum	32 37 S	142 56 E	MANARA	Occurrence
Gypsum	32 36 S	143 10 E	MANARA	Boola Boolka Lake occurrence
Gypsum	32 41 S	143 25 E	MANARA	Occurrence
Gypsum	32 57 S	143 50 E	MANARA	Occurrence
Gypsum	34 03 S	143 37 E	BALRANALD	Occurrence
Gypsum	34 32 S	143 35 E	BALRANALD	Occurrence
Gypsum	35 35 S	142 34 E	SWAN HILL	Occurrence
Gypsum	35 03 S	143 12 E	SWAN HILL	Occurrence
Gypsum	35 08 S	143 03 E	SWAN HILL	Occurrence
Gypsum	35 10 S	143 07 E	SWAN HILL	Occurrence
Gypsum	36 04 S	143 42 E	ST ARNAUD	Occurrence, Boort area
Gypsum	36 08 S	143 41 E	ST ARNAUD	Occurrence, Boort area
Gypsum	32 36 S	144 08 E	IVANHOE	Gypsum Palace open cut mine
Gypsum	32 33 S	144 03 E	IVANHOE	Occurrence
Gypsum	32 39 S	144 17 E	IVANHOE	Occurrence
Gypsum	32 45 S	144 58 E	IVANHOE	Occurrence
Gypsum	32 34 S	144 51 E	IVANHOE	Occurrence
Gypsum	32 45 S	144 42 E	IVANHOE	Occurrence
Gypsum	32 46 S	144 47 E	IVANHOE	Occurrence
Gypsum	32 50 S	144 23 E	IVANHOE	Occurrence
Gypsum	32 50 S	144 07 E	IVANHOE	Occurrence
Gypsum	32 53 S	144 57 E	IVANHOE	Occurrence
Gypsum	32 55 S	144 29 E	IVANHOE	Occurrence

TABLE 44. ctd. (page 3 of 3)

Commodity	*Latitude*	*Longitude*	*Map Sheet*	*Remarks*
Gypsum	32 59 S	144 51 E	IVANHOE	Occurrence
Gypsum	32 51 S	145 04 E	IVANHOE	Occurrence
Gypsum	36 07 S	144 13 E	BENDIGO	Occurrence
Limestone	35 18 S	139 26 E	BARKER	Abandoned quarry
Limestone	34 01 S	139 40 E	RENMARK	Morgan Quarry – abandoned
Limestone	34 11 S	139 58 E	RENMARK	Waikerie Quarry
Limestone	34 11 S	140 20 E	RENMARK	Abandoned quarry
Limestone	34 39 S	139 37 E	RENMARK	Blanchetown Quarry
Magnesium	33 20 S	146 20 E	CARGELLIGO	Magnesite open cut mines at Lake Cargelligo
Manganese	35 43 S	139 45 E	PINNAROO	Kangaroo Flat manganese prospect, abandoned quarry
Molybdenum	36 26 S	146 34 E	WANGARATTA	Occurrence
Salt (NaCl)	35 21 S	139 20 E	BARKER	Occurrence
Salt (NaCl)	34 35 S	142 08 E	MILDURA	Occurrence
Salt (NaCl)	35 02 S	141 43 E	OUYEN	Pink Lakes occurrence
Salt (NaCl)	35 15 S	141 22 E	OUYEN	Occurrence
Salt (NaCl)	36 21 S	141 56 E	HORSHAM	Occurrence – salt lakes
Salt (NaCl)	36 25 S	141 55 E	HORSHAM	Occurrence – salt lakes
Salt (NaCl)	36 37 S	141 53 E	HORSHAM	Lake Wyn Wyn occurrence
Salt (NaCl)	36 43 S	141 48 E	HORSHAM	Mitre Lake occurrence
Salt (NaCl)	36 49 S	141 51 E	HORSHAM	Occurrence – salt lakes
Salt (NaCl)	36 50 S	141 51 E	HORSHAM	Occurrence – salt lakes
Salt (NaCl)	37 00 S	141 43 E	HORSHAM	Occurrence – salt lakes
Salt (NaCl)	37 04 S	141 45 E	HAMILTON	White Lake area – occurrence
Salt (NaCl)	35 00 S	142 47 E	SWAN HILL	Occurrence
Salt (NaCl)	35 00 S	142 54 E	SWAN HILL	Occurrence
Salt (NaCl)	35 05 S	142 49 E	SWAN HILL	Occurrence
Salt (NaCl)	35 10 S	142 50 E	SWAN HILL	Occurrence
Salt (NaCl)	35 15 S	142 49 E	SWAN HILL	Lake Tyrrell salt deposits
Salt (NaCl)	35 04 S	143 13 E	SWAN HILL	Occurrence
Salt (NaCl)	35 13 S	143 05 E	SWAN HILL	Occurrence
Salt (NaCl)	35 17 S	143 04 E	SWAN HILL	Occurrence
Salt (NaCl)	35 19 S	143 02 E	SWAN HILL	Lake Timbooram occurrence
Salt (NaCl)	35 17 S	142 58 E	SWAN HILL	Lake Washpool occurrence
Salt (NaCl)	35 23 S	143 08 E	SWAN HILL	Occurrence
Salt (NaCl)	35 25 S	143 35 E	SWAN HILL	Occurrence
Salt (NaCl)	35 32 S	143 47 E	SWAN HILL	Occurrence
Salt (NaCl)	35 39 S	143 52 E	SWAN HILL	Third Lake & Reedy Lake occurrences
Tin	36 05 S	146 53 E	WANGARATTA	Occurrence – alluvial
Tin	36 20 S	146 36 E	WANGARATTA	Occurrence
Tin	36 16 S	146 46 E	WANGARATTA	Occurrence
Thorium	35 34 S	143 34 E	SWAN HILL	Occurrence in Lake Boga Granite

rington & Anderson, 1970; Laws & Heisler, 1967). The Merreti and Coombool Members of the Monash Formation locally contain lithic sands but, generally form a confining layer separating the basal Cretaceous from the basal Tertiary. These units are all of limited distribution and have not been investigated for groundwater (Reed, 1980).

Cainozoic. The Murray 'sedimentary' Basin extends to the coast, but, as a result of its structural configuration, the Murray 'groundwater' Basin is almost entirely separated from the Southern Ocean, and is thus a closed groundwater basin (Brown, 1988, 1989; Evans & Kellett, 1988, 1989; Evans & others, in press). Almost all surface drainage and groundwater flow is internal and is directed towards the topographically depressed central-western depocentre, which effectively forms a groundwater sump. With the exception of some spillage over the concealed Padthaway Basement Ridge in the south-west, groundwaters are effectively trapped within the aquifer systems of the basin, and can only escape by discharge to the surface, where they are removed by evaporation or by leakage into the river systems. Consequently, the thin stratigraphic sequence is largely water-saturated, the aquifer systems of the basin have only limited additional groundwater storage capacity, and groundwater levels are generally close to the surface. In the central-west, the Murray River acts as an effluent drain, and provides the only natural conduit for removal of excess salt from the basin. Salts generated by evaporation are thus trapped within the basin, and groundwaters in the uppermost aquifers have become progressively more saline as a result of several past periods of high groundwater levels and evaporation during the past 0.5 Ma.

The Cainozoic succession of the basin can be translated into a number of regional aquifers, each

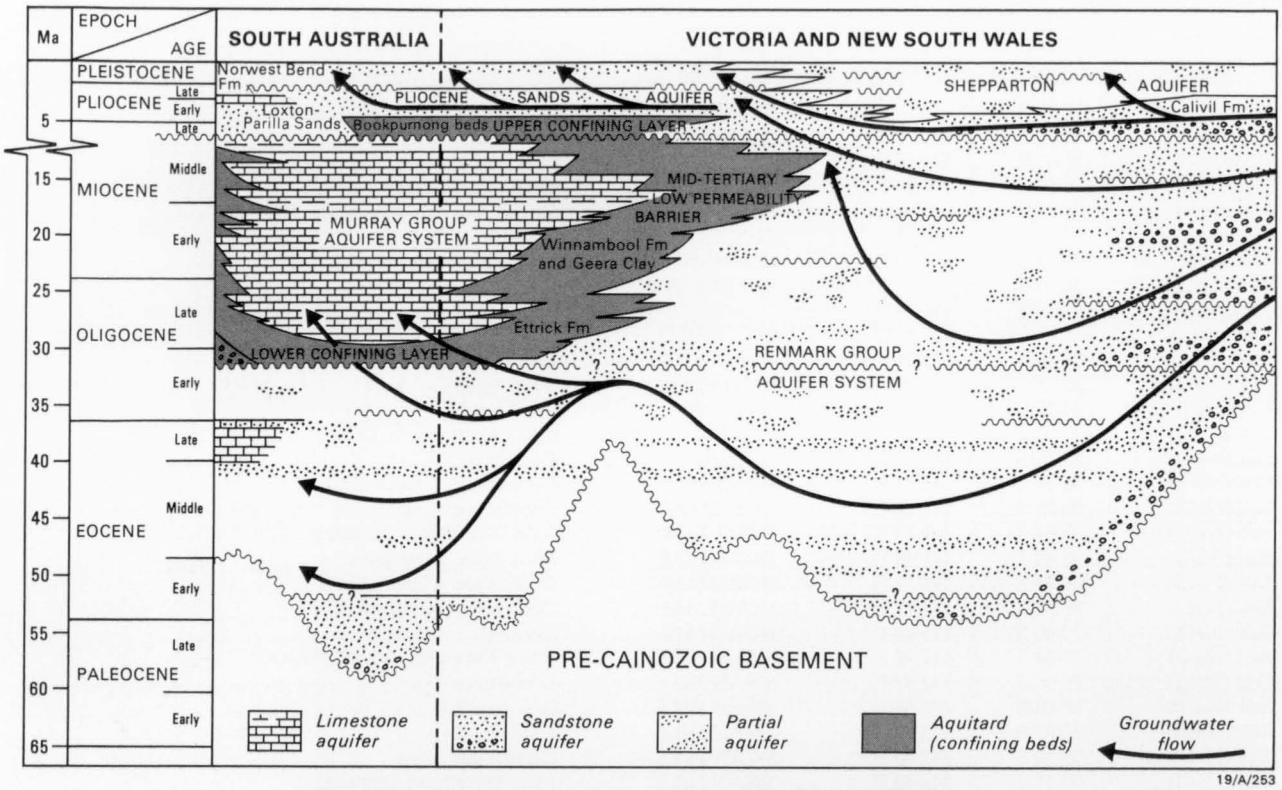


Fig. 172. Regional aquifer systems of the Murray Basin.

with distinctive characteristics (Fig. 172; O'Driscoll, 1960; Lawrence, 1967, 1975, 1976e; Brown, 1985, 1988, 1989; Evans, 1988; Leonard, 1988a,b; Evans & others, in press; Evans & Kellett, 1988, 1989). The Renmark Group aquifer system at the base of the succession is separated from the overlying Murray Group aquifer system in the west by a Lower confining layer consisting of the Oligocene Ettrick Formation, and a Mid-Tertiary low permeability barrier of the Winnambool Formations and the Geera Clay. Towards the southwest, the Murray Group aquifer system is overlain by the near-surface Pliocene Sands aquifer system, but farther to the east and north is overlain by a Late Tertiary Upper confining layer, mainly of the Bookpurnong beds. To the north and east, the Upper confining layer locally merges with regressive components of the Winnambool Formation and Geera Clay of the Mid-Tertiary low permeability barrier. The Pliocene Sands aquifer system is a composite body consisting of Loxton–Parilla Sands in the west and Calivil Formation in the east. Beneath the Riverine Plain and adjacent highland valleys the Pliocene Sands aquifer system directly overlies the Renmark Group aquifer system, and is in turn overlain by the Shepparton Formation partial aquifer system. Groundwater in each of the aquifers increases in salinity downflow, towards the main depocentre in the central-west, and the most saline waters occur in the uppermost Pliocene Sands aquifer system in the west. Quaternary aquifers are of importance in some coastal areas to the southwest of the basin. These are not discussed below, but are also locally experiencing salinity problems.

Renmark Group aquifer system

At the base of the succession, the confined Renmark Group aquifer system is a composite aquifer–aquitard complex (Fig. 172; Brown, 1989). It includes the ?Paleocene to Eocene Warina Sand, Eocene sand and carbonate of the Buccleuch beds, and sandy silt and sand within the Eocene to Middle Miocene Olney Formation. The Warina Sand is confined to the deeper central-western parts of the basin, and the Buccleuch beds to southwestern areas. Most of the Renmark Group aquifer system (informally referred to as the 'Renmark Aquifer') occurs within the Olney Formation, and therefore underlies almost the entire Murray Basin (Plate 5). The aquifer system is confined where overlain by the Ettrick Formation (Lower confining layer), as well as by the Winnambool Formation and Geera Clay (Mid-Tertiary low permeability barrier) in the deeper western parts of the basin. Farther east and north, however, it is only semi-confined beneath the Pliocene Sands aquifer system and the Shepparton

Formation partial aquifer system, beneath the Riverine Plain (Fig. 172).

The Warina Sand component forms a high-yielding semi-confined sub-system, consisting of clean sand characterised by high porosity and permeability (Lawrence, 1975, 1976e; Leonard, 1988a,b). Woolley & Williams (1978) noted that basal sand (some of which they called Warina Sand) beneath the Riverine Plain holds relatively fresh water in eastern areas, but this becomes increasingly saline towards the west. Groundwater movement is mainly towards the central-west of the basin.

The Olney Formation consists of fluvial sand and silt bodies forming a stacked series of locally discontinuous, but generally interconnected aquifers, separated by laterally discontinuous layers of lower permeability. Locally, the aquifers can be subdivided into independent sub-systems with distinct pressure and salinity characteristics. In the Pooncarie–Ivanhoe–Balranald area, for example, Kellett (1989) has identified three sub-systems. The upper and lower sub-systems are sandy, whereas the middle sub-system is generally finer-grained. Aquifer (and local aquitard) characteristics vary considerably within the Renmark Group aquifer system.

In the highland valleys of northern Victoria and beneath eastern and southern areas of the Riverine Plain, the Renmark Group aquifer system produces good quality water, which is being locally utilised (M.A. Reid, Rural Water Commission of Victoria, personal communication, 1989). Beneath the Riverine Plain, salinities increase towards the central-west, particularly within upper components, and exceed 10 000 mg/l T.D.S. west of Balranald (Woolley & Williams, 1978). In western areas of the basin, the upper components hold saline waters, whereas local sub-systems have reasonably fresh water at depth (e.g. Kellett, 1989). Much of this water is suitable for stock purposes, and the aquifer system is artesian in some low-lying central-western areas. In western areas of the Murray Basin, few water bores currently utilise the aquifer system, however, because of its depth of burial and the presence of saline water in upper parts of the aquifer system. In South Australia, salinities increase from southeast to northwest towards the Murray River (Barnett, 1983, 1989b). The aquifer system is largely unexploited in South Australia because of the availability of good-quality water from the overlying aquifer systems, but southwest of the Marmon–Jabuk Scarp, where the shallow aquifer is saline, the deeper aquifer is used for stock and domestic purposes (O'Driscoll, 1960; Barnett, 1983, 1989b). At the northwest margin of the basin in South Australia, recorded salinities increase southwards towards the Murray River (Barnett, 1981b).

Variations in the geometry of the Renmark Group aquifer system result in flow disruption and may have contibuted to development of some of the surface discharge complexes of the basin (Fig. 172).

Lower confining layer

In the southwest of the basin, the fluviolacustrine sediment of the Renmark Group aquifer system is separated from the overlying shallow-marine limestone of the Murray Group aquifer system by the thin calcareous clay of the Ettrick Formation (Lower confining layer; Plates 7, 8; Brown & Radke, 1989). In this area, the Ettrick Formation appears to be both sufficiently thin (10–30 m thick) and permeable to allow relatively fresh waters from the river systems of the northwest Victorian highlands to recharge the Murray Group aquifer system, in part via laterally equivalent parts of the Renmark Group aquifer system.

Mid-Tertiary low permeability barrier

To the north and east, the thin sediment of the Lower confining layer merges with the basal sediment of the considerably thicker Mid-Tertiary low permeability barrier (thicknesses in excess of 100 m; Plates 9, 10, 11; Brown & Radke, 1989). The barrier consists of calcareous clay of the Ettrick and Winnambool Formations, as well as silt and silty clay of the Geera Clay. The younger sediments form a partial envelope around the eastern and northern limits of the Murray Group aquifer system, separating it from the underlying and laterally equivalent sediments of the Renmark Group aquifer system, as well partly separating it from the overlying Pliocene Sands aquifer system (Fig. 172). The Geera Clay in particular, forms a major barrier to groundwater flow, which in some areas can be related to the surface discharge of saline waters. Total porosities of between 40% and 50% (based on pore fluid content) have been measured in these unconsolidated sediments (W.R. Evans, BMR, personal communication, 1988). However, visual estimations of interparticle porosity within the marginal-marine Geera Clay indicate that effective porosity (and permeability) is very low, and predominantly consists of remnant interparticle porosity of only a few percent within infilled burrows (Radke, 1987). Minor channel sands within the Geera Clay locally retain porosity and per-

meability, but most are now tight due to cementation during the course of diagenesis.

Murray Group aquifer system

The Murray Group aquifer system (Fig. 172; Plate 12) consists of skeletal calcarenite, and micritic limestone of the Oligocene–Miocene Murray Group (Gambier Limestone, Mannum Formation, Morgan Limestone, Pata Limestone, and Duddo Limestone). The aquifer system is up to 150 m thick, although most bores penetrate only the uppermost few metres. In the west, a high skeletal content in combination with the local addition of quartz sand has resulted in high intergranular porosities. Farther to the north, east and southeast, the limestone is increasingly fine-grained, but is still highly permeable (e.g. Crawford & O'Driscoll, 1962). In southwestern areas, solution cavities have developed within the aquifer system, as recorded in some boreholes and by the presence of surface sinkholes. The aquifer is generally viewed as a single system, although Barnett (1983) described prominent layers of marl in the Karte (PINNAROO) area which locally divide the aquifer into two sub-systems.

The Murray Geoup aquifer system is probably the most productive and economically important in the Murray Basin and is utilised by several thousand boreholes. No surface drainage reaches the Murray River from the northwest Victorian highlands, and south of the Murray River it is partly recharged by infiltration of relatively fresh groundwaters draining from the northwest Victorian highlands towards the river (Lawrence, 1975; Barnett, 1983, 1989b), and partly by vertical recharge. South of the river, in northwestern Victoria and adjacent areas of southeastern South Australia, it therefore holds a large resource of good quality water, and is extensively exploited for stock and domestic purposes, as well as for town water supplies and local irrigation schemes. Concern over the management of the resource led to the implementation of the 'Border Groundwaters Agreement' between the Victorian and South Australian Governments (e.g. Ingram & Stadter, 1988; Lawrence & others, 1988). Salinities in the Murray Group aquifer system increase away from the recharge areas in the south, and decrease with depth. A local area with low salinities (600 mg/l to 1400 mg/l TDS) occurs in the upper part of the aquifer system in the Karte area (Fitzpatrick, 1953; Cobb, 1979), and may be related to local recharge from the surface (Barnett, 1983). Northwest and west of the Murray River, salinities locally exceed 20 000 mg/l TDS (Herraman, 1978; Barnett, 1989b), particularly in bores where the limestone interfingers with marl of the Winnambool Formation. North of the Murray River, the aquifer system is partly recharged by infiltration through the highly saline Pliocene Sands aquifer system, although some relatively low salinity areas occur where the aquifer is recharged by small creeks flowing from the adjacent Mount Lofty Ranges at the western and southwestern margins of the basin (Barnett, 1980, 1981a,b, 1989b).

Upper confining layer

In the southwest of the Murray Basin, over the up-faulted Pinnaroo Block, the Murray Group aquifer system is unconfined and directly overlain by the near-surface Loxton–Parilla Sands. Farther east and north it is confined beneath thin, but fine-grained, sediments of the Bookpurnong beds forming the Upper confining layer (Plate 14), as well as by regressive components of the Winnambool Formation and Geera Clay of the Mid-Tertiary low permeability barrier (Fig. 172). In places, the Upper confining layer directly overlies the Mid-Tertiary low permeability barrier, thereby increasing the effectiveness of the permeability barrier separating the upper Renmark Group and basal Pliocene Sands aquifer systems from the Murray Group aquifer system.

Pliocene Sands aquifer system

The Pliocene Sands aquifer system (Fig. 172) is a composite system consisting of the near-surface Loxton–Parilla Sands in the west and buried Calivil Formation in the east. Beneath the Riverine Plain and adjacent highland valleys to the east and north, the sands of the aquifer system form an extensive sheet, and are semi-confined beneath the Shepparton Formation partial aquifer system and directly overlie the Renmark Group aquifer system. At the basin margins, coarse sands and gravels of the Calivil Formation, particularly in the 'deep lead' systems, are highly porous and permeable, and provide a major pathway for migration of groundwater from the highland valleys to the Riverine Plain. In New South Wales, the aquifer system is being used near the basin margins in the Hillston area adjacent to the Lachlan River, in the Griffith–Leeton area adjacent to the Murrumbidgee River, and in the Corowa–Tocumwal–Cobram area adjacent to the Murray River. In Victoria, the aquifer is important in the upper Murray, upper Goulburn, Campaspe and Lod-

don Valleys. Farther into the basin, however, beneath much of the Riverine Plain, permeabilities decrease and the groundwater becomes increasingly saline (Woolley & Williams, 1978). In addition, the clearance of natural vegetation and development of irrigation schemes have resulted in increased infiltration into and through the Shepparton Formation, causing a rapid rise in pressure levels in the Calivil Formation in many eastern areas. Beneath the mid-Loddon Valley (Macumber 1978a,b,c,e, 1983), for example, the aquifer is now artesian and saline waters discharge to the surface. Macumber (1978c) has demonstrated that the aquifer is particularly sensitive to minor climatic fluctuations, and in years of high rainfall the level of water in the aquifer has risen considerably, whereas an equivalent 'natural' fall is not experienced in years of drought.

In the Mallee regions of the western Murray Basin, the shallow-marine, marginal-marine, and fluvial sands of the Loxton–Parilla Sands form an unconfined aquifer system. The system is locally overlain by discontinuous fine-grained lacustrine sediments of the Blanchetown Clay. The Loxton–Parilla Sands are largely absent over the southwestern margins of the basin, where the unit has been particularly subject to deflationary erosion and re-mobilisation into Quaternary duneforms. West of the Murrayville Monocline, the Loxton–Parilla Sands are unsaturated over the up-faulted Pinnaroo Block in the southwest (with the exception of a few areas near Pinnaroo). Elsewhere, however, the Loxton–Parilla Sands are 60 to 100 m thick and contain highly saline shallow groundwater. This flows towards the central-western depocentre, and locally intersect the land-surface of the Mallee region, forming groundwater discharge lake complexes and salinas in low-lying areas (Fig. 143; McLaughlin, 1966; Macumber, 1980, 1983; Teller & others, 1982; Bowler & Teller, 1986). The distinctive suite of landforms, consisting of sand plains, crystalline gypsum and gypsite flats, gypsite dunes, salinas, and stranded lake floors, which characterise the groundwater discharge complexes was given the name 'boinka' by Macumber (1980). Potentiometric surfaces in the underlying Murray and Renmark Group aquifer systems tend to be higher than the water table in the Pliocene Sands aquifer system. Groundwater movement in the Pliocene Sands aquifer system is towards the Murray River, which acts as an effluent drain into which saline waters seep – resulting in greatly increased river salinities where the river is eroded into the Loxton–Parilla Sands. At Mallee Cliffs, for example, significant increases in river salinity have been attributed to seepage from the Pliocene Sand aquifer system (Forth & others, 1988). Similarly, increased salinity in the Wimmera system can also be related to discharge from the Loxton–Parilla Sands (Anderson & Morison, 1988, 1989).

North of the Murray River, in South Australia, regional groundwater salinities exceeding 25 000 mg/l TDS have been recorded in the Loxton–Parilla Sands, although fresher waters occur in local recharge areas adjacent to modern creeks draining the flanking Mount Lofty Ranges (Barnett, 1980, 1981a,b, 1989b). In northwest Victoria and adjacent areas of South Australia and New South Wales, regional salinities range from 14 000 to 35 000 mg/l (Evans, 1988), but extremely high salinities have been recorded in reflux brines beneath both active and currently inactive groundwater discharge lake complexes. In these areas, salts which have been concentrated by evaporation in the lake systems, have diffused back into the regional aquifer, where they have accumulated in gravity-settled brines. Beneath the Noora discharge complex (RENMARK), for example, salinities of up to 93 000 mg/l have been noted (Reed, 1980). At Lake Tyrrell (SWAN HILL), salts are concentrated by summer evaporation, but sink back into the underlying Pliocene Sands aquifer system following winter rains (Macumber, 1983). Adjacent to Lake Tyrrell, regional salinities range from 30 000 to 50 000 mg/l TDS, but salinities in the reflux brine beneath the lake from 200 000 to 260 000 mg/l TDS (Teller & others, 1982).

A number of active and fossil groundwater discharge sites in the Mallee region are locally entrenched within thin, discontinuous, fine-grained lacustrine sediments of the Quaternary Blanchetown Clay. Several of these sites in low-lying areas, are thought to be underlain by Blanchetown Clay, and are currently being investigated as potential evaporation basins for the disposal of saline waters from irrigation and groundwater interception schemes. At many sites, however, the Blanchetown Clay is of variable thickness, frequently with interbedded sands and is only locally impermeable. Each proposed site therefore requires careful investigation to determine the likely rate and effects of recharge into the underlying Pliocene Sands aquifer system (e.g. Newman & Collingham, 1988).

Shepparton Formation partial aquifer system

The Shepparton Formation partial aquifer system is a composite aquifer–aquitard complex. Fine to coarse sand bodies within the formation are an essentially unconfined aquifer system (Fig. 172), consisting of shoe-string sand bodies with varying degrees of lateral and vertical interconnection. The aquifer system is of major importance in the eastern and southeastern Riverine Plain, where groundwater mounds have developed beneath several irrigation schemes, resulting in waterlogging of root systems and local salinisation problems.

Beneath the southeast Riverine Plain, salinities near the major rivers are locally in the range 100 to 500 mg/l TDS, but generally range from 900 to 4000 mg/l TDS (Tickell, 1977a; Tickell & Humphrys, 1980, 1987), whereas away from the rivers and towards western areas of the Riverine Plain, salinities range up to 12 000 mg/l TDS (Woolley & Williams, 1978). In the Riverine Plain in N.S.W., the aquifer system is used for stock and domestic purposes east of Hay (Woolley & Williams, 1978).

Groundwater management and salinity problems

As noted above, because of its structural configuration, the Murray Basin is a closed groundwater basin, within which groundwater flow is towards the main depocentre, in central-western areas. An exception occurs in the extreme south, where flow is towards the Otway Basin. These aquifer systems are largely water-saturated and have little additional storage capacity. Consequently, groundwaters can rise rapidly to the surface, and both groundwaters and salts generated by surface evaporation are trapped within the basin.

Salts are continually imported into the Murray Basin by rainfall (Blackburn & McLeod, 1983), surface water, and groundwater infiltrating via Tertiary sediments beneath the valleys of adjacent highland areas. These sources initially consist of relatively fresh waters, although salinisation is also occurring in adjacent highland areas (e.g. Dyson & Jenkin, 1981; Dyson, 1983; Jenkin & Dyson, 1983; Lewis, 1985; Wagner, 1986; Junor, 1988; Charman & Junor, 1989). Most salts within the Murray Basin, however, have accumulated due to evapotranspiration in areas where groundwater levels have risen to within the capillary zone, as well as at sites of groundwater discharge – a process which has been greatly enhanced during a number of periods of high groundwater levels and semi-arid to arid climatic conditions during the past several hundred thousand years. Some salt has been flushed from the basin by the Murray River, and some has been re-distributed elsewhere by aeolian processes, but much has been recycled back into underlying shallow aquifer systems, where it remains trapped within the basin. Consequently, the groundwater systems are layered, with the most highly saline waters occurring within the uppermost near-surface aquifers, which have become progressively more saline during past periods of 'natural' high groundwater levels, surface evaporation and salinisation. Many currently active, as well as 'fossil' (currently inactive) groundwater discharge lake complexes are now underlain by highly saline brines. Part of the reason for the build-up of salinity over the past 0.5 Ma has therefore been climatic, with periods of slightly higher rainfall alternating with those of relative aridity with inherited high groundwater tables and consequent salinisation (Bowler & Wasson, 1984; Bowler, 1986, 1988). In the past 100 years, however, salinisation has developed because groundwater levels have risen to within the capillary zone in response to European land management practices, rather than because of climatic change (Bowler, 1988). Rates of increased recharge/discharge associated with various types of native vegetation and with land clearance have been investigated by Allison & Hughes (1978, 1983), Allison & others (1985, 1988), Leaney & Allison (1986), Cook & others (1988), and Jolly & others (1988). Rates of groundwater movement, and groundwater sources have been investigated using naturally occurring Chlorine-36 isotopes by Calf & others (1988), and Davie & others (1988, 1989). Broadscale revegetation has been proposed as a means of minimising recharge (e.g. Mossis & Thomson, 1983; Marcar & others, 1988; Williams & others, 1988), but, as discussed by Dumsday & others (1988, 1989), this may be neither economic nor practical, apart from at a local scale.

The Murray Basin is one of internal surface drainage, and the Murray River acts as an effluent drain providing the only connection between the basin and the ocean to the south. Unfortunately, however, the quality of the river water needs to be maintained to supply both Adelaide and a number of economically important irrigation schemes, as well as for environmental reasons (Mackay & others, 1988). Consequently, the use of this natural conduit for removal of saline water is politically and socially un-

acceptable. Given that the salinity problem is caused by rising groundwater levels, then a potential solution involves lowering the groundwater table below the capillary zone. This involves development of a basin-wide strategy for disposal of excess saline water (Evans, 1988a,b, 1989). A number of local solutions have been adopted, although some of these simply involve shifting the problem from one part of the basin to another. In many irrigation districts, tiled drainage has been installed to capture excess irrigation water and prevent the build-up of salts by evaporation. Along tracts of the river near irrigation districts (particularly in South Australia), excess water returns are currently stored in evaporation ponds within which saline waters are concentrated. These ponds are located on the river floodplain adjacent to the main channel, and are flushed during periods of flooding of the river. Unfortunately, they result in the displacement of underlying highly saline groundwater to the Murray River. At present the most attractive solution involves the pumping of saline waters into natural evaporation basins already containing saline lake deposits. In western areas, some of these are underlain by a seal of Blanchetown Clay. Such schemes have been developed for the disposal of irrigation waters at Noora in South Australia and Wakool in New South Wales (Brereton & Hoey, 1988). Other schemes, such as at Mallee Cliffs (Forth & others, 1988) and Woolpunda (Barnett, 1984; Siebenaler, 1987, 1988a,b; Telfer, 1987a,b, 1988, 1989; Newman & Collingham, 1988), involve the interception of saline groundwater before it seeps into the river system.

Salinity problems within the near-surface Shepparton Formation are now of major concern throughout the irrigation districts in the southeast Riverine Plain and adjacent areas (e.g. Ife, 1983), and a number of investigations have been undertaken to understand both the systems and processes involved, as an aid to development of management solutions (Macumber, 1966, 1968, 1973, 1978b,c,e; Lawrence, 1975; Tickell, 1977a, 1982, 1983; Tickell & Humphrys, 1979, 1980, 1985, 1987; Bartley & Reid, 1987; Brinkley & others, 1988; Ife, 1988a,b,c; Gill, 1988a,b, 1989; Ife & Hoxley, 1988; Nolan & Brinkley, 1988; Nolan & others, 1988; Olshina, 1988a,b; Pratt & others, 1988; Potts, 1988a,b; Pratt, 1988; Prendergast & Heuperman, 1988; Roderick, 1988; Shugg, 1988; Trewhella, 1988, 1989; Williamson, 1988; Reid, 1989; and Bartley, in press). Similar hydrogeological investigations have been undertaken in the Mallee (Gloe, 1947; Johns & Lawrence, 1961, 1964; Lawrence, 1966, 1971, 1973, 1975; Shugg, 1976; Rowan, 1971; Jenkin, 1979, 1983; Macumber, 1980, 1983; Finlayson, 1986; Stewart, 1986, 1987, 1989; Duran & Nott, 1988; Eaton, 1988; Nott, 1988a,b,c,d,e,f,g,h, 1989; Thorne & Hoxley, 1988; Willocks, 1988; Thorne & others 1990). Nahm (1982) compiled a 1:1 000 000 scale map showing the groundwater water resources of Victoria, described in Nahm (1987). In New South Wales, hydrogeological investigations have been undertaken by Gibbons & others (1972), Woolley & Williams (1978), and Williams (1983a,b, 1985). Investigations, concerned with the management of groundwater and salinisation in South Australia, are documented in reports by O'Driscoll (1956, 1960), Cramsie (1969), Roberts (1970a,b), Waterhouse (1974), Reed (1980), Barnett (1980, 1981a,b, 1983, 1985, 1988a,b,c, 1989a,b,c), Edwards (1981c), Selby (1981), and Howles (1986).

In order to understand the systems in which the salinity problems have developed, much of the research undertaken in the basin has involved investigation of the sedimentary processes resulting in the formation of surface geomorphic features, such as lunettes and groundwater discharge lakes. As noted previously, it is apparent from the distribution of such features that salinity problems have been considerably worse in the recent geologic past, despite the fact that these problems have been greatly exacerbated by current land-use practices. Mapping of fossil groundwater discharge features can thus be used as a predictive technique in the identification of those areas likely to be next affected by salinisation.

A number of reviews of the salinity problem, as well as strategies for managing the groundwater resource and minimising the problem, have been documented in recent years. These include Boucaut (1975), ACIL Australia (1981, 1983), Gutteridge, Haskins & Davey (1983), Dwyer Leslie (1984), Macumber (1984a), Salinity Committee of the Victorian Parliament (1984); Macumber & Fitzpatrick (1987), Murray–Darling Basin Ministerial Council (1987b, 1988), Paterson (1987), Salt Action (1987), Blackmore (1988), Brown & Evans (1988), Brown & others (1988), Lakey & Williams (1988), Lawrence (1988c), Leslie (1988), Macumber & Dyson (1988), Paterson & Sutherland (1988), Victorian Department of Water Resources (1988), Woolley (1988), and Lakey & others (1989). Evans (1988a,b, 1989) reviewed the effectiveness of the various techniques used to dispose of saline water. A number of local and regional groundwater models have been developed to simulate the natural groundwater system, as an aid to management (e.g. Williamson,

1982a,b, 1983, 1984; Duran & Nolan, 1987; Barnett, 1988c, 1989c; Kalf, 1988; Oakes, 1988). Part of the management strategy devised to cope with the problems of salinisation involves understanding the systems and processes in which these problems have developed. This includes understanding the relationships between aquifer geometry, groundwater flow patterns, and the distribution and character of surface discharge.

Relationships between aquifer geometry, groundwater flow, and the development of 'natural' groundwater-discharge sites

Groundwaters in the Murray Basin tend to flow towards the greatest tectonic subsidence and thickest sediments in the central-west. En-route, however, they pass through a number of low-lying subsidiary 'basins' as well as areas underlain by buried basement ridges. Numerous active and inactive groundwater discharge complexes have developed within the low-lying areas of the basin during the past 0.5 Ma of arid and semi-arid climatic conditions. Major discharge complexes have been identified in the Manara, Darling/Darling Anabranch, Scotia, Pinecamp, Willandra, Hatfield, Kerang, Tyrrell, Buloke, Manangatang, Walpeup, Raak, and Noora areas (Fig. 143). Discharge at these sites is partly due to groundwater 'outcrop' within low-lying areas of tectonic subsidence, and partly to local disruption of the regional flow of groundwater towards the central-western depocentre of the basin. This disruption is caused by variations in the geometry of underlying aquifers, as a result of the interaction of concealed basement structure and basin lithostratigraphy.

An arcuate zone of inactive saline lake and gypsum–clay pellet lunette complexes occurs around the western margins of the Riverine Plain (Fig. 143). This zone overlies the Renmark Group aquifer system where it thins significantly to the west, partly because of the structural influence of basement ridges (Fig. 4) and partly because of lateral stratigraphic replacement of the aquifer by the Mid-Tertiary low permeability barrier (Fig. 172). At the northwestern margin of the Plain, for example, the Hatfield discharge complex (Figs 136, 150) developed over a zone where the Renmark Group aquifer system thins from greater than 300 m to less than 50 m over an up-faulted but concealed basement ridge (Iona Ridge) of the adjacent Ivanhoe Block (Fig. 4, Plate 5). Groundwater flow is forced to the southwest, where it is further impeded by the presence of thick Geera Clay of the Mid-Tertiary low permeability barrier (Plate 9). At times of high groundwater pressures in the past, this probably resulted in discharge into the overlying aquifer system, and locally to the surface. The Hatfield discharge complex is currently inactive, but in the future it may develop salinity problems, if groundwater levels continue to rise. Similar 'fossil' discharge complexes are recorded in the landscapes of the Manara region to the north (Fig. 143). These overlie thick sediments of the Blantyre Trough (Fig. 22), and were probably activated at times of high aquifer pressures when groundwater flow to the south was impeded, because the aquifers thin over the relatively shallow basement rocks of the up-faulted Ivanhoe Block (Fig. 4).

Examples of aquifer thinning due to lateral changes in sediment type occur where the Geera Clay forms a subsurface barrier to groundwater movement in the Renmark Group aquifer system, resulting in the partial diversion of flow into the overlying Pliocene Sands aquifer system (Fig. 172), and locally to the surface as groundwater discharge complexes. Beneath the southwest extremity of the Willandra Lakes (Fig. 143), the Renmark Group is laterally replaced by thick Geera Clay. The lake system has developed over the southwesterly trending Willandra Trough (Fig. 4), flanked to the southeast by the up-faulted but concealed Iona basement ridge and to the northwest by the similarly up-faulted Neckarboo Ridge. Southwesterly groundwater flow is largely within the Willandra Trough; and at times of higher groundwater levels in the past, the disruption to flow, caused by the replacement of the Renmark Group aquifer system by the Geera Clay, almost certainly contributed to surface discharge and origin of the lake system at that particular site. The lunette flanking the northeastern margin of the Chibnalwood lakes, at the southwestern end of the Willandra Lakes system (Figs 135, 142), consists almost entirely of clay pellet material, indicating that seasonal discharge and evaporation of saline groundwaters dominated the lake during periods of lunette formation (Dare-Edwards, 1982; Bowler, 1983). In contrast, the lunette which flanks Lake Mungo (farther to the northeast in the Willandra Lakes system) consists of a mixture of clay and sand-dominated layers – the sand layers were possibly derived from lake-shore beaches deposited when the lake was dominated by fresher surface waters (Bowler, 1971, 1983).

In southwestern New South Wales, the salinas and stranded lake deposits of the Scotia and

Pinecamp areas (Fig. 143) occur in low-lying areas of tectonic subsidence (elevations as low as 22 m in places), which partly overlie the concealed Tararra Trough. These salinas are flanked by lunettes of gypsiferous clay pellet sediments, indicating domination by groundwater processes. The discharge lake complexes are underlain by relatively thin sediments (60–80 m) of the Pliocene Sands aquifer system, further underlain by thick low permeability sediments of the Bookpurnong beds and Geera Clay (120–160 m thick), and that in turn by Renmark Group. Southwesterly groundwater flow from the Pliocene Sands and Renmark Group aquifer systems in the north is disrupted by the presence of the low permeability units. The underlying Renmark Group aquifer system is fully saturated, and groundwater flows over the concealed permeability barrier into the near-surface Pliocene Sands aquifer system. The present flow of groundwater is sufficient to maintain the watertable above the ground surface within low-lying areas, where it forms the modern discharge lake complexes.

Groundwater influences are not currently active within the extensive ephemeral lake systems associated with the Darling River and Darling Anabranch farther north (Figs 140, 141, 166), but most lake floors there are, however, flanked to the northeast by extensive 'nested' lunettes. These contain superimposed sand and clay pellet layers, which record a past lacustrine history of alternate surface and groundwater-dominated phases. Saline groundwater discharge is thought to have been active during past periods when climatic conditions were arid, but the saline groundwater table, inherited from a preceeding wetter climatic phase, was at a higher level than at present. The additional influence of underlying structural control is also seen in the string of lakes in the Menindee region, which directly overlies and parallels the concealed southwesterly trending Menindee Trough.

At the southern margin of the basin, the Buloke discharge complex (Fig. 143) may have developed from disruption of basinward groundwater flow due to the stratigraphic replacement of the Renmark Group aquifer system by the Geera Clay. Farther north, the Lake Tyrrell (Fig. 147) and Manangatang (Figs 1, 170) discharge zones are underlain by the near-surface Pliocene Sands aquifer system, and occur in low-lying areas of tectonic subsidence, overlying the concealed Tyrrell Basin (Fig. 4). Groundwater flow out of the Tyrrell Basin is partly impeded because the Pliocene Sands aquifer system is underlain by thick low-permeability sediments of the Bookpurnong beds and Geera Clay, and partly because of the presence of relatively shallow basement up-faulted to the west of the Tyrrell Fault.

Farther west, in the Mallee regions of northwest Victoria, highly saline groundwaters of the Loxton–Parilla Sands locally intersect the ground surface in a number of low-lying areas of tectonic subsidence, such as in the Walpeup–Raak Plains (Figs 143, 146), where groundwater discharges to topographic depressions (elevations 30–40 m), underlain by relatively thick sediments. Groundwater flow towards the central-western depocentre, to the northwest, is impeded by the presence of a concealed northeasterly trending basement block, up-faulted to the northwest of the Danyo Fault (Fig. 4). The aquifer system thins significantly over the up-faulted area (elevation 100 m to greater than 130 m), which was named the 'Sunset Strip' by Macumber (1980). Farther to the northwest, the Noora discharge complex (Fig. 143) has developed between stranded ridges of Pliocene Loxton–Parilla Sands, in a low-lying area of subsidence flanked to the southwest by the up-faulted Pinnaroo Block.

A further significant example of stratigraphic control on groundwater flow and surface discharge occurs in the south and east, where the highly permeable coarse sands and gravels of the Calivil Formation become increasingly fine-grained, and also laterally interfinger with finer-grained sediments of the basal Shepparton Formation and Loxton–Parilla Sands. The permeability of the Calivil Formation thus decreases to the north and west, where it also contains increasingly saline groundwater. The increased salinity is thought to have accumulated by refluxing through the partial aquifer system of the Shepparton Formation during past 'natural' periods of high groundwater levels, and increased evaporation at the surface. In the southeastern Riverine Plain of northern Victoria, increased recharge to the Shepparton Formation partial aquifer system (Macumber, 1978b,c, 1983) during the past 100 years of clearance of natural vegetation and development of irrigation schemes has also resulted in increased recharge to the 'deep-lead' aquifer system (Calivil Formation; Macumber, 1978b,c, 1983; Tickell, 1982, 1983; Arad & Evans, 1987; Tickell & Humphrys, 1987), thereby re-activating the 'natural' system. In the lower Loddon Valley, the resulting increase in groundwater pressures, in combination with the presence of the low permeability sediment, has resulted in the reactivation of saline groundwater discharge at Bears Lagoon and Barr Creek, and lakes in the Kerang region (Macum-

ber, 1968). Similarly, areas such as the Corop–Colbinabbie fossil groundwater discharge site in the Goulburn Valley are close to re-activation (M.A. Reid, Rural Water Commission of Victoria, pers. comm., 1989).

Coal

No coal is currently mined in the Murray Basin, but groundwater investigations undertaken over the past hundred years have revealed the presence of Upper Permian, Cretaceous and Tertiary coals (Fig. 171). The economic viability of Upper Permian sub-bituminous coal in the Oaklands Basin, beneath the southeastern Murray Basin, is currently under investigation. A number of small Tertiary coalfields at the southwestern margins of the basin are being re-examined. In addition, several billion tonnes of Tertiary brown coal have been identified by CRA Exploration in the Renmark Group, in the Kerang–Cohuna region at the southern margin of the Murray Basin (Brunker & others, 1986).

Upper Permian

Low-sulphur, sub-bituminous Upper Permian coal deposits of the Coorabin Coal Measures were first discovered in 1915 in a water bore in the Oaklands Basin beneath the southeastern Murray Basin (Jones, 1920). Production from Lanes Colliery commenced in 1917, but continued only intermittently until 1959 when mining ceased owing to recurrent flooding by groundwater (Smith, 1961a,b; Bembrick, 1974; Driver, 1975). The Lanes Shaft Coal Member is up to 9 m thick, but the thickest mined seam was 2.4 m thick and occurs beneath an overburden of 73 m. Early drilling undertaken in the southern Oaklands Basin by the N.S.W. Department of Mineral Resources (Jones, 1935) and by BMR (Sturmfels, 1950; Fisher, 1951) delineated the southern margin of the basin, indicating that coal occurs at depths of between 40 and 200 m. Geophysical surveys (Thyer & Vale, 1952; Petty Geophysical, 1961; Richardson, 1962; Bluestone, 1969; Kemmis, 1970), including two good-quality reflection profiles (Palmer, 1977) have been used to further define the limits of the coal basin. The results of geophysical investigations have been summarised by McIntyre (1976). Analyses of coal samples on behalf of B.P. Petroleum Development Australia Pty Ltd are recorded in Strauss & others (1974). Anglo-American Corporation (Australia) Ltd drilled several holes in 1970 (Anglo-American, 1970; Powell & Driver, 1971). The N.S.W. Department of Mines subsequently undertook a drilling program in 1973/74 (Palese, 1974), and drilled a further six exploratory bores to the north of Jerilderie in 1980. The 1980 program defined the northern limits of the basin, and encountered coal seams between 4.8 and 11.2 m thick beneath overburdens of between 220 and 350 m (Yoo, 1981a, 1982). Coal reserves in the southern part of the basin total several thousand million tonnes (Sturmfels, 1950; Muran, 1970; Powell & Driver, 1971), while total inferred in-situ reserves in the north are estimated at about 2.9 billion tonnes (Yoo, 1981a).

The stratigraphy of the coalfield was defined by the Standing Committee on Coalfield Geology (1976; O'Brien, 1981, 1986). Within the Coorabin Coal Measures, three distinct point-bar sequences are each capped by coal beds: the Lanes Shaft Coal Member, Coreen Creek Coal Member and Nowranie Creek Formation. The palynology of the coals was described in a series of reports by Morgan (1975a,b, 1976a,b, 1977a,b), and indicates that deposition occurred intermittently over a number of Permian Stages (see 'Upper Permian').

Most of the coal deposits of the Oaklands Basin are preserved above the underlying Ovens Graben, but some extend beyond the margins of the graben, and Upper Permian coal deposits have also recently been identified in the Numurkah Basin, southeast of Deniliquin (e.g. Gates, 1986; Brinkley & others, 1988). Investigations have recently been undertaken by Pacific Coal Pty Ltd, Coal Cliff Collieries Pty Ltd, and Mitsubishi Development Pty Ltd to assess the feasibility of renewed production from several potential sites in the Oaklands Basin. Borehole and other data from these investigations are stored in the archives of the Geological Survey of New South Wales. Supplementary data are also available in borehole records of the New South Wales Department of Water Resources.

Cretaceous occurrence

Carbonaceous sediments with leaf litter debris are common within the Lower Cretaceous Monash Formation (and equivalent Millewa Group) in the Renmark Trough area, but the only known Lower Cretaceous coal-bearing interval was intersected by N.S.W. D.M. Umalee No.1 exploration bore, which was drilled in 1980 near Ivanhoe beneath the northern margin of the basin (McMinn, 1981; Yoo, 1981b).

Tertiary deposits

Groundwater investigations have revealed poorly known but extensive lignitic coal within mid-Tertiary sediments of the Olney Formation of the Renmark Group. No currently economic deposits have as yet been located, but the discovery of the subeconomic Bower Coalfield in 1902, the Moorlands Coalfield in 1910, and the Anna Coalfield in 1927, at the western margin of the basin, has encouraged continuing if intermittent exploration for coal in South Australia (Johns, 1975). It was not until 1979, however, that Western Mining Corporation discovered the Kingston deposit of 985 million tonnes of Middle Eocene lignite, in contiguous sediments to the north of the Gambier Embayment (Fig. 171; Meyer, 1983; Harris, 1985). This discovery resulted in re-newed interest in the potential of the Murray Basin. Minor deposits at the western margin of the basin have been drilled and re-assessed by Bryan (1972), Buonaito (1980), Theiss Brothers (1980), Coffey & Partners (1982), Bubner (1983), Moore (1984), Coleman & Associates (1984), Lewis (1984), CRA Exploration (1985b), Gould & others (1985), Theiss–CSR (1986), and Western Mining (1987). The Moorlands Coalfield consists of at least six small basins with seams averaging 6.5 m, with proven reserves of 31 million tonnes beneath 30 m of overburden (McGarry, 1953; Johns, 1961, 1975; Rogers, 1980a). The main coal seam at the Anna Coalfield is 4.3 m thick and reserves are estimated at 68.2 million tonnes (Kress & others, 1978). The Moorlands deposits have been differentiated as the Moorlands Lignite Member (Ludbrook, 1961a; Harris, 1966; see Table 12).

In Victoria, groundwater bores beneath the Riverine Plain have encountered widespread, but thin and discontinuous coal seams within Eocene to mid-Miocene fluvio-lacustrine and paralic sediments. In addition, CRA Exploration have recently discovered major deposits in the Kerang, Torrumbarry and Echuca regions of northern Victoria (Brunker & others, 1986). In the Kerang region, a lower seam is up to 15 m thick and occurs at depths of between 155 and 175 m, and an upper seam is up to 40 m thick and at depths of between 100 and 130 m. In the Cohuna region to the east, the lower seam is up to 20 m thick at depths of between 175 and 200 m, and the upper seam is up to 25 m thick between 95 and 120 m. Brunker & others (1986) estimated that a minimum of several billion tonnes of brown coal, with a relatively high ash content, occur at depths of less than 150 m. They noted that minimum overburden-to-coal ratios of 4:1 apply to much of this resource. Preston (in press) subsequently estimated that 30 000 million tonnes of coal are present. A similar drilling program by CRA Exploration, farther west in the Horsham area, in 1982, failed to locate any significant brown coal in the Olney Formation.

Deposits, equivalent to those of the southern Murray Basin in Victoria, probably occur beneath adjacent areas of the New South Wales sector of the Riverine Plain, where some bores have intersected cumulatively thick intervals of carbonaceous sediments. In New South Wales, however, the availability of alternative sources of low-cost coals, as well as the isolation of the Murray Basin from potential markets, has resulted in a low level of interest in exploration. The known occurrences are thought to be discontinuous, thin, and too deep to be of economic significance. The distribution of water bores, known to have encountered a cumulative thickness of greater than 10 m (generally over a 90 to 120 m interval), are shown on Figure 171. In the Griffith region, irregular overlapping lenses of brown coal occur at depths between 42 and 88 m (Pels, 1960b; Wynn, 1962; Frenda, 1965; Wood, 1965). Reserves of around 200 million tonnes have been estimated in the region (Whitehouse, 1981). Thick sequences of coal also appear to be particularly well developed in the Deniliquin–Wanganella–Wakool region, where several boreholes have encountered a cumulative thickness of several tens of metres of coal. In contrast, an exploration bore drilled near Booroorban, south of Hay failed to encounter any coal, although carbonaceous material occurred throughout the Olney Formation (Yoo, 1981c). Farther west, the Olney Formation occurs at increasing depths of burial and has consequently been intersected by correspondingly fewer bores. In the Menindee region in the northwest, a number of uranium exploration bores have intersected minor carbonaceous sediments at depth (Wecker, 1971a; Morgan, 1973), and Comserv Blackgate No.1 (Comserv, 1980) encountered 14.7 m of lignite at a depth of 163 m (Baker, 1982). No significant deposits have been identified at shallow depths, but it seems possible that areas near the basin margin may be prospective for small deposits, similar to those in fault-bounded depressions near the western margin in South Australia.

Analyses indicate that the carbonaceous Tertiary sediments of the Murray Basin have undergone varying degrees of coalification; they are mainly of soft low-rank lignitic brown coal, and peat of woody plant

debris. They generally have a low calorific value and high moisture, sulphur, salt, and ash contents. Many peats are still fibrous and are currently undergoing decay, so that when cored the odour of marsh gas has been reported (Yoo, 1981a).

Scattered carbonaceous debris occurs within the Warina Sand beneath the Olney Formation, and within the coarse-grained fluvial components of the Calivil Formation above the Olney Formation. However, no significant intersections of coal have been reported. Beneath the western Riverine Plain, for example, thin carbonaceous intervals were encountered in Woodside Balranald No.1 (Ludbrook, 1962a). These are thought to have been deposited in fluvio-deltaic environments transitional to the Late Miocene–Early Pliocene marine and marginal-marine environments farther west.

Palaeoclimatic conditions in the Eocene to Mid-Miocene were conducive to the generation and preservation of extensive coal deposits, whereas, in contrast, palaeoclimates during the Late Cainozoic are thought to have been characterised by increasing seasonal aridity (Bowler, 1982; Truswell & others, 1985; Macphail & Truswell, 1989; Martin, 1989), so that only minor carbonaceous sediments were deposited. As discussed above (see 'Cainozoic Sedimentation Patterns' – Chapter 14), coal preservation may have been enhanced during rise of both sea-level and groundwater levels. Differential tectonic subsidence has also preserved thicker sequences in some areas relative to others. Several of the thicker deposits occur in small fault-bounded depressions where peat accumulation was enhanced by a combination of tectonic subsidence, high rainfall, high groundwater tables, and paludal swamp and marsh conditions.

In summary, Tertiary coal-bearing sediments occur at shallow depths around the basin margins, but under much of the Riverine Plain are concealed beneath at least a minimum of 80 to 130 m of overburden, and beneath central-western areas occur at depths locally in excess of 300 m. In most areas, potential mining is constrained by unfavourable depths of burial beneath water-saturated Tertiary sediments. However, only a small proportion of the many thousands of boreholes have penetrated the coal-bearing succession, and consequently the exploration potential of large areas remains unknown, and it seems likely that further deposits will eventually be identified.

Uranium

Some aspects of the geological setting of the fluvial-deposited lithologies of the Murray Basin appear superficially similar to those of other basins with roll-front uranium deposits. This similarity has encouraged exploration for uranium, but no indications of mineralisation have as yet been detected. In the Padthaway ridge area, Pacminex Pty Ltd identified a single anomaly with 30 ppm uranium oxide in Quaternary sediments at a depth of 35.5 m (Rogers, 1980a). The northwestern margin of the basin, in both South Australia and New South Wales, was investigated by airborne radiometrics, water bore sampling and extensive auger and rotary drilling programs. The results of work undertaken by Mines Administration Pty Ltd in South Australia are recorded in Wecker (1971b), Bryan (1972), and by Sedimentary Uranium N.L. (Hall, Relph & Associates, 1971). Similar surveys were undertaken in adjacent areas of N.S.W. (Wecker, 1971a,b; Morgan, 1973; Degeling, 1974). The scintillometer surveys indicated low-level radiometric anomalies over claypans, and the drilling identified minor radioactive anomalies associated with carbonaceous intervals in the upper Olney Formation – however, no uranium was detected. Similar surveys beneath the southeastern Murray Basin also failed to identify mineralisation (Wecker, 1971c; Coles, 1972; Mines Administration, 1972; Haynes, 1973; Techmin, 1973; Esso Australia, 1974; Western Mining Corporation, 1978a,b; Brunker & others, 1986).

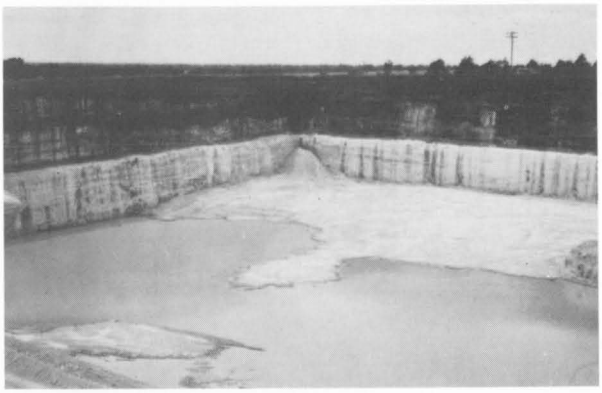
Torbernite has been identified on joint planes in a Devonian granite exposed in an aggregate quarry near Lake Boga (SWAN HILL); but again, no economic deposits are known (Chambers, 1958; Thomas, 1958; Bowen, 1976, 1988; Birch, 1977, 1988).

Gold

In the late 19th and early 20th centuries, auriferous alluvial placer deposits were extensively mined from coarse sands and gravels of the 'deep lead' systems within the tributary highland valleys of northern Victoria (Canavan, 1988). The discovery of several of these deposits was associated with short-lived gold-rushes, but most were rapidly worked out by individuals or small groups. Many gold deposits occured within stranded Eocene to Pliocene high-level alluvial gravels, whereas others are in shallow alluvial and eluvial sediments of the modern drainages (Swift, 1950; Whiting & Bowen, 1976,

1988). Many buried deposits are associated with the Calivil Formation which forms the youngest of several gold-bearing 'deep-lead' systems (Hunter, 1909). These can be traced northwards beneath the Riverine Plain, but flooding of mine shafts prevented exploitation of the deeper and more basinward gold. In recent years, experimental chemical leaching techniques have been attempted, but possible pollution problems – in what is one of the major aquifer systems of northern Victoria – have thus far prevented commercial development. Some gravel beds within the rivers of tributary highland valleys are currently being worked by small-scale operators using underwater vacuuming and sifting techniques involving high-volume hydraulic pumps and sluices.

The general locations of the deep-lead deposits are shown on the BENDIGO and ST. ARNAUD 1:250 000 geological maps, while detailed maps and site descriptions of the auriferous placer deposits, and descriptions of exploration activity, are given in Murray (1884a,b, 1896, 1898), Stirling (1894), Moon (1895), Whitelaw (1895, 1898), Baragwanath (1903, 1923, 1946), Gregory (1903), Dunn (1905, 1908, 1909, 1912a,b), Hunter (1903, 1907, 1909), Wilkinson (1907), Herman, (1921), Hunter & Mulvaney (1937), Swift (1950), Clappison, 1969; Flett (1970), Techmin (1973), King (1977), McKenna & Partners (1978), Essex Minerals (1980–1983), Triad Minerals (1983), Williams (1983), and Canavan (1988). Semi-precious gemstones, including garnet, sapphire and zircons are also associated with the deep lead deposits (Stone, 1976, 1988). Stanniferous placers also occur locally within the gravels (Cochrane, 1971), particularly to the east of the Murray Basin, where they are of economic significance.



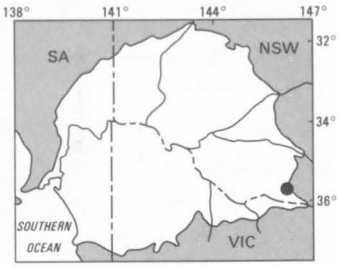


Fig. 173. Open cut kaolin mine near Coorabin (JERILDERIE); upper dark layer of Shepparton Formation, over white layer of kaolin (?Torrumbarry Clay).

Limestone

A number of skeletal calcarenite, calcisiltite, micritic limestone, dolomite, and calcrete units crop out in the western part of the Murray Basin. Some of these have been exploited economically as sources of building stone, lime, or road aggregate.

Murray Group limestones. Outcrops of the Oligocene–Lower Miocene Gambier Limestone in the Gambier Embayment of the Otway Basin (Fig. 63) are widely used as a building stone, but outcrops in the Murray Basin are too weathered to be suitable. The Naracoorte Limestone (upper Member of the Gambier Limestone), which occurs only on the southernmost part of the Pinnaroo Block, near the town of Naracoorte, is unsuitable for use as building stone, but has been quarried for lime in the past, and is also used for road screenings (Ludbrook, 1961a). The Mannum Formation crops out in lower parts of the Murray River Gorge, and has been quarried as building stone near the town of Murray Bridge (Ludbrook, 1961a). The Morgan Limestone is locally used as a building stone, although thickness of overburden and variability of texture limit this application. The unit crops out in the upper Murray River Gorge, and was extensively quarried for building stone near Overland Corner (Ludbrook, 1961a; Shepherd & Olliver, 1987). The Pata Limestone is a largely subsurface unit, difficult to distinguish from the Morgan Limestone. It is not generally suitable for use as building stone, but may have significance as potential road aggregate.

Norwest Bend Formation. The Norwest Bend Formation is a highly fossiliferous, locally sandy, limestone, grading into a coquinoid limestone characterised by oyster concentrations (Fig. 101). It is restricted to a small area of the western Murray Basin (Fig. 100), but crops out prominently in the Murray River cliff tops between Overland Corner and Blanchetown. It has in the past been used as building stone, under the local names 'Ramco Stone' and 'Waikerie Freestone' (Ludbrook, 1961a; Farrand, 1985; Scott & others, 1987), and is also widely used as road aggregate, particularly from 'Fossil Quarry' near the town of Morgan, and from a quarry near the Marne River Valley, southwest of Swan

Reach.

Calcrete. The extensive calcrete deposits of the western Murray Basin are commonly utilised as road aggregate, particularly in the Mallee region, where consolidated surface sediments are rare (see 'Paving and Construction Materials').

Kaolin

In the Oaklands area of the southeastern Murray Basin, deposits of white kaolinitic clay are mined by both open-cut and underground methods – mainly for use in the manufacture of refractories. The clay varies in quality, but the mined refractory deposits consist of creamy white clay with low plasticity and high titanium oxide content. Coarse-grained components are used in the manufacture of bricks (Bembrick, 1974). In the Victorian highlands, other kaolinitic clays are used for sewer pipes, roofing tiles and pottery. Kaolinisation probably occurred at various times during the Late Cretaceous and Cainozoic, and the age of many kaolinitic deposits is uncertain. Some younger deposits may have formed during development of the Mologa surface of weathering of Macumber (1978a) – these appear to be associated with the Calivil Formation of Late Miocene–Early Pliocene age, and can be assigned to the Torrumbarry Clay. Most deposits were formed by erosion of weathering profiles in the flanking highland areas, and were redeposited in highland valleys and adjacent fluvial environments of the southeast Riverine Plain. Large pits in the Coorabin area of the Oaklands Basin, for example, consist of lenticular lenses of kaolin within a quartzose sand sequence (?Calivil Formation). The deposits occur beneath an overburden of 10 to 20 m (Fig. 173). At Axedale, in the Campaspe Valley near Bendigo, kaolin deposits have been preserved beneath Newer Volcanic flows (Chambers, 1949; Ferguson, 1976, 1988). Eocene clay in southeast South Australia was described by Kingsbury (1955).

Heavy minerals

LANDSAT scenes, aerial radiometric surveys, and borehole data indicate the presence of a potentially prospective, former shallow-marine shelf strandplain extending beneath the Mallee region of western Victoria, adjacent areas of South Australia, and western New South Wales. The shallow-marine and strandplain sediments (Loxton–Parilla Sands) have been found to contain local concentrations of heavy minerals. In the Kerang and Gredgwin Ridge areas, Macumber (1978a) reported the presence of heavy minerals bands up to 1 m thick, intercalated within cross-bedded fine to coarse micaceous quartz sand exposed in quarries. These were interpreted as beach or shallow-marine sands, and consist of an ultra-stable suite of zircon (10–30%), ilmenite (40–65%), rutile (5–11%), leucoxene (2–7%), with smaller percentages of tourmaline, monazite, and chromite (Macumber, 1983).

In 1977, BMR undertook stratigraphic drilling in the Edenhope and Nhill–Kaniva areas of western Victoria (Colwell, 1977). Thin bands, with up to 20% of heavy minerals, in ridges within the strandplain complex, were found to consist of a mineralogically mature suite of 50–70% opaques, 15–30% tourmaline, 3–5% rutile, and 5–15% zircon. Heavy minerals of these mature inland occurrences have a high proportion of stable to ultrastable multicyclic components. Williams (in press) noted that most concentrations are located at the southern margins of the strandplain. Extensive inland areas of the strandplain are under investigation for heavy minerals. Some of this data is confidential, but reports are available by Masters (1983), Balmoral Resources (1984–1987, 1986–1987), Bromley (1984), Matthias & others (1984), Barclay & others (1985), Aberfoyle Resources (1986–1987, 1987), CRA Exploration (1986, 1987, 1988a,b,c,d,e,f,g, 1989), Leah (1986, 1987a,b, 1988), Stanley & Catach (1986), Aberfoyle–Balmoral Resources (1987–1988), Doe (1987), Teakle (1987), Wright (1987), and Allnutt (1988). A major deposit – which may prove to be one of the world's largest – has been discovered in fine-grained marine sands at Drung South (HORSHAM; Fig. 171) by Wimmera Industrial Minerals Pty Ltd, a subsidiary of CRA Exploration Ltd. Preliminary estimates suggest the deposit has at least 1000 million tonnes of ore averaging 3% heavy minerals, with approximately 50% ilmenite and significant quantities of leucoxene, rutile, anatase, monazite and xenotime. A further 4000 million tonnes of lower grade ore is also thought to occur in the region. Investigations are continuing, and the feasibility of mining is currently being examined.

The heavy mineral content of the calcareous stranded beach-ridge complexes of the Pleistocene Bridgewater Formation has been investigated by Harrison (1975), Larson (1973, 1974), and Colwell (1976, 1978, 1979). Colwell (1979) noted that the concentrations of heavy minerals are generally low – due in part to dilution by a high biogenic carbonate detrital component. In the Padthaway region, selected intervals within the underlying Loxton–

Parilla Sands have up to 1.2% of heavy mineral consisting of 25–45% magnetite/ilmenite, 5–20% leucoxene, 5–25% zircon, 5–30% tourmaline, and 0–10% amphibole, epidote, rutile, and garnet. Colwell (1976, 1979) suggested that these were locally derived, mainly from basement granitoids of the Padthaway Ridge area. Reports on exploration activity in the modern beach sediments, the Bridgewater Formation, and coastal areas of the Loxton–Parilla Sands strandplain are presented in Hillwood (1960), Harrison (1975), North Broken Hill (1977), Morris (1978), CRA Exploration (1985a,b), Richards & Jenke (1986), Aberfoyle Resources (1987), Bluck (1988a,b), and reviewed by Belperio & Bluck (1988).

Gypsum

Gypsum deposits, as crystalline selenite, and pelletal sand/silt-sized gypsite are widely distributed throughout the western Murray Basin. They occur within both active and 'fossil' groundwater discharge complexes, and are mainly associated with the Upper Pleistocene to Holocene lacustrine and lunette deposits of the Yamba Formation. Minor selenite is also associated with upper layers of the Pleistocene Blanchetown Clay. Several deposits of relatively pure gypsite have been mined for the manufacture of cement (77% minimum purity) and plasterboard (75% minimum), while relatively impure deposits (50% minimum) have been extensively exploited for local agricultural purposes in the form of a soil additive. Most deposits are only marginally economic and have been only intermittently worked. Cartage costs are a significant factor in determining the economic viability of deposits. Those located in close proximity to railway lines or the larger towns have been worked, whereas widespread deposits in the lower Darling River/Darling Anabranch region are relatively isolated and remain unexploited.

Locally extensive deposits of cream to yellow-brown gypsite of varying degrees of purity occur within some fossil lunette systems ('Qdl' associated with 'Qly' and 'Ql') and locally attain a thickness of several metres. Within adjacent fossil and active saline lake floors gypsum deposits are often crystalline, but rarely attain thicknesses of greater than 1 m. Some of the larger fossil groundwater discharge complexes consist of stranded gypsum flats (locally referred to as 'Kopi Plains') overlain by low-lying deflated and nested lunettes, and gypsite dunes.

As previously described (see Yamba Formation and Tyrrell beds), the deposits formed by evaporation of saline groundwaters at surface discharge sites. Most of the gypsum has been derived from regional groundwaters within the underlying Pliocene Sands aquifer system, although at least some gypsum may have been recycled from the uppermost Blanchetown Clay (Morris, 1985).

South Australian deposits have been described by Jack (1921), and Johns (1952a,b, 1953, 1954, 1969). Lunette deposits are currently worked at Morgan, where reserves have been estimated at 3.1 million tonnes of gypsum sand (71% pure), and 0.9 million tonnes of gypsum silt (73% pure). Additional reserves of 1.53 million tonnes gypsite (69% pure), with an additional 1.37 million tonnes of crystalline gypsum (41% pure), occur in the adjacent lake floor. An estimated 149 000 tonnes are suitable for cement and plasterboard manufacture, while the remainder is only suitable for agricultural purposes. The results of a number of investigations of the deposits at Morgan have been reported in Whitten (1962), Moffitt & Hosking (1962), Olliver (1967), and Morris (1983a, 1985). At Ramco West, Layton & others (1987) identified a potential resource of 10 million tonnes. The Gluepot gypsum deposit (southern CHOWILLA, near Waikerie) has reserves estimated at 116 000 tonnes (50–75% purity), and 115 000 tonnes (averaging 58% purity; McCallum, 1984). Barnes & Warren (1983a,b) estimated the Blanchetown gypsum deposits (associated with Blanchetown Clay; Downie & others, 1987) to contain reserves totalling 29.6 million tonnes (81–85% pure). The deposits at Cragie Plains were described by King (1952), Willington (1956), Forbes (1961), and Morris (1983b, 1985). Known pockets of high-grade materials at Cragie Plains have been exhausted and no mining is currently undertaken. The remaining lunette deposits have reserves of 243 000 tonnes, but are of low purity (43%) and only 14 000 tonnes are thought to be suitable for agricultural purposes (Morris, 1985). Hiern (1971) estimated that the lunette at the Parcoola deposits consisted of 10 million tonnes of gypsum (60–70% purity), while the adjacent lake floors contained up to 5 million tonnes of crystalline gypsum. At Rotten Lake reserves were estimated at 0.8 million tonnes of gypsum (60–80% purity) within lake sediments (Miles, 1951; Johns, 1953). The lunette deposit at Cooke Plains consists of up to 3 million tonnes of gypsum (80% purity; King, 1952; Rogers, 1980a; Gould & others, 1985). Blissett (1970) reviewed the mineral resources, including sources of gypsum, in the Upper Murray area of South Australia.

Occurrences associated with playa lake deposits in northwest Victoria have been described by

Thomas (1947), Lawrence (1970, 1976b), Cooney (1988), and Lawrence & Inan (1988). A complex of small salt lakes near Underbool (Pink Lakes) were described by Cane (1962). Other mined deposits occur at Nypo, at Nowinga West and Hattah West in the Raak Plains area, Cowangie, and Lake Hindmarsh. Deposits have also previously been worked at Tempy, Lake Boga, Boort and Waitchie. At Raak Plains gypsum deposits are washed and screened to retain the larger gypsum crystals for plaster production. Mineral specimens of celestite and associated glauberite from the Mallee area have been described by Sutton (1978, 1982, 1983). The hydrogeological context of the Raak Plains deposits has been described by Macumber (1983), while the sedimentological setting of the evaporitic deposit at Lake Tyrrell has been described by Teller & others (1982) and Bowler & Teller (1986).

Fossil and currently active groundwater discharge complexes occur throughout the western New South Wales sector of the basin, but most of the associated gypsum deposits are considered to be sub-economic, and unsuitable for industrial (as opposed to agricultural) uses (Adamson, 1985; Cameron, 1988a). In the past, deposits have been worked at Gol Gol, located a few kilometres northeast of Mildura, where production commenced in 1928. Major deposits have also been worked at the Manara Mines, and at a number of sites near Ivanhoe, all of which are located in close proximity to the Broken Hill–Ivanhoe railway line (Wynn, 1967; Holmes & others, 1982). The Gypsum Palace deposit near Ivanhoe has been estimated to have at least 3 million tonnes of good quality gypsum. Deposits occur beneath the northwest Riverine Plain, and in the lower Darling/Darling Anabranch region, but apart from minor local use, these are not currently exploited, owing to the variable quality and remoteness of the region from potential markets (Adamson, 1985).

Halite

At present, during periods of summer evaporation, ephemeral halite crusts are precipitated over relatively small salinas within many of the currently active groundwater discharge complexes of the Murray Basin. In most cases, these deposits are re-dissolved during periods of rainfall. In the Pink Lakes complex in the Underbool–Linga region of northwest Victoria, a permanent layer of salt is seasonally overlain by an ephemeral surface crust. This deposit was harvested as early as 1866 when teams of Afghan camel trains transported rock salt (Hardy, 1914, 1936; Owen, 1943; Cane, 1962; McLaughlin, 1966). The most extensive deposit in the basin occurs within Lake Tyrrell, where halite is precipitated during summer evaporation and re-dissolved by winter rain. Thick deposits are not preserved at the surface because the bulk of the halite is dissolved and diffused into an underlying brine (see 'Tyrrell beds' – Table 37). A salt works has operated intermittently at the southwestern margin of the lake (McLaughlin, 1966). Salt crusts precipitated during the summer months were harvested from the lake surface, and stockpiles then purified and bagged as rock salt. Other salinas producing salt, at various times, are located at Lake Kunat, Lake Kelly, Lake William, Little Lake, Spectacle Lake at Raak Plains, in a number of other small lakes near Kerang and Swan Hill, as well as near Douglas and Dimboola farther west (Bain, 1949; Lawrence, 1970, 1976c; Inan, 1988; locations listed in Table 44). In the future, salts may be harvested from some of the evaporation basins established in the basin to dispose of saline water (e.g. Walker, 1983)

Paving and construction materials

Towards the margins of the Murray Basin, a variety of basement rocks and Tertiary gravels are imported into the basin as road aggregate and construction materials (e.g. King, 1977). In western Victoria and at Mount Shank south of Mount Gambier, these include scoria and tuff from the Upper Cainozoic 'Newer Volcanics' (Barnes & McCallum, 1975; McKenzie, 1977; Wilkinson, 1977). In the Padthaway Ridge area, small basement exposures of Kanmantoo Group metasediments, Ordovician granitoids and acid volcanic are quarried as aggregate (e.g. Paine & others, 1984). Within the basin, Devonian granite is quarried at Lake Boga, and ?Devonian metasedimentary rocks have been quarried from an outcrop on BOOLIGAL. Tertiary gravels of the ?Calivil Formation are mined at Urana (JERILDERIE), while other Tertiary gravels in the Murray River Valley are worked near Wodonga (WANGARATTA).

Many of the unsealed all-weather roads of the western Murray Basin are paved by crushed calcrete. In southwestern areas, this is obtained from thick calcrete sheets at the surface (Qca), whereas farther east and north, near-surface sheet and nodular calcretes are found within, and at the base of, the Woorinen Formation. Supplies are readily extracted from numerous bulldozed pits located adjacent to

the roads. The material from these pits is often locally referred to as 'kunkar'. Minor oolitic ironstone is also used near Pooncarie (Byrnes & others, 1985).

Many shires throughout the basin maintain small sand and gravel pits for the provision of construction materials. In the Riverine and southern Wimmera Plains, sand pits are located in stranded channels of the Shepparton and Coonambidgal Formations. Sand pits have also been developed in fluvial-derived aeolian source-bordering dunes (Qad), as well as in sandy lunette deposits (e.g. Barmah sand hills adjacent to former Lake Kanyapella on BENDIGO; Bowler & Harford, 1966a; Bowler, 1978a).

Tertiary limestones of the Murray Group and Norwest Bend Formation, exposed in the Murray River Gorge at Murray Bridge, Mannum, Marne River Valley, Morgan and Waikerie have been quarried for use as building stone, as well as for concrete and paving aggregate. The limestone quarry at Overland Corner (Cornerstone), for example, has operated intermittently since at least 1858, and 6000 tonnes were removed between 1945 and 1958. Shepherd & Olliver (1987) recommended that the quarry be incorporated into the nearby 'Overland Corner Hotel' historic site, and that future quarrying be restricted to stone required for the restoration of existing historic buildings. Scott & others (1987) reviewed the history of quarrying of Norwest Bend Formation for building stone in the Ramco area, from where over 10 000 tonnes had been removed by 1982. In South Australia, construction sands, including fine aggregate suitable for concrete production, are obtained from quarries in the Loxton–Parilla Sands at Loxton, and Spring Cart Gully near Berri (RENMARK; see Fig. 94; Keeling, 1984). Materials from these deposits, in addition to Quaternary sands at Murbko (RENMARK), provide the main sources of filter sand and gravel in South Australia (Scott, 1983, 1985). In the Morgan area, Scott (1980) identified sources of construction sands in the Coonambidgal Formation and Bunyip Sand. Scott & Olliver (1987) identified reserves of 24 000 tonnes of coarse construction sands intercalated within Blanchetown Clay in the McLelland sand pit near Waikerie. In the Sugar Loaf Hill quarry, 18 km northeast of Barmera, 120 000 tonnes of dolomite aggregate (Bungunnia Limestone), and 18 000 tonnes of sand (Loxton–Parilla Sands) were produced between 1949 and 1985 (Crettenden, 1986). Reserves are estimated at 930 000 tonnes of dolomite and 3.8 million tonnes of sand.

In the southwest, Firman & Rogers (1975), Johnson (1976), and Nicol (1977) reviewed the availability of construction materials and engineering geology in the proposed Monarto town. In the lower southeast of South Australia, the results of investigations of construction sands have been summarised by Keeling & others (1985). The deposits are believed to consist of reworked Loxton–Parilla Sands and are located at Naracoorte (1.5 million tonnes; Johns, 1962; Keeling & others, 1982, 1985), Wepar (120 000 tonnes; Keeling, 1982), Comaum Forest Reserve (reserves of 3.5 million tonnes; Keeling, 1983a,b), and Allen's sand quarry (80 000 tonnes; Keeling, 1983c). Numerous pits in the Pleistocene Bridgewater Formation are used for road rubble throughout much of southeast South Australia (Flint, 1984). Martins (1981) reviewed the mineral resources of the Calperum land management area, and Thompson (1982) those of the Lameroo District Council area. A review of the use and value of both private and public construction materials in the Griffiths and Wentworth Shires in New South Wales are in Cameron (1987, 1988a). Gorbert & Corkery (1978) and Corkery (1979) investigated the suitability of sand northwest of Griffith for glass making.

Hydrocarbons

During the past three decades, only limited exploration for hydrocarbons in the Murray Basin and underlying infrabasins has been undertaken. Reasons for this are discussed below. With the exception of minor gas shows, and one possible oil show, no significant indications of hydrocarbons have as yet been encountered. However, the results obtained to date need to be viewed in the context of an inadequately explored basin.

Petroleum exploration

The first petroleum exploration well in Australia was drilled early this century, in the coastal Coorong area to the south of the Murray Basin. Gas was subsequently encountered in Cretaceous sediments in the Gambier Embayment of the adjacent Otway Basin, which continues to attract exploration attention. In the Murray Basin, however, an initial phase of exploration activity began only in the mid-1950's and continued until the late 1960's. Much of this early activity established that the extensive Murray Basin succession is thin and generally overlies shallow basement (Chapter 4). Thick sedimentary sequences are confined to infrabasins in northwestern and western areas, and the Oaklands and Numurkah Basins beneath the southeastern

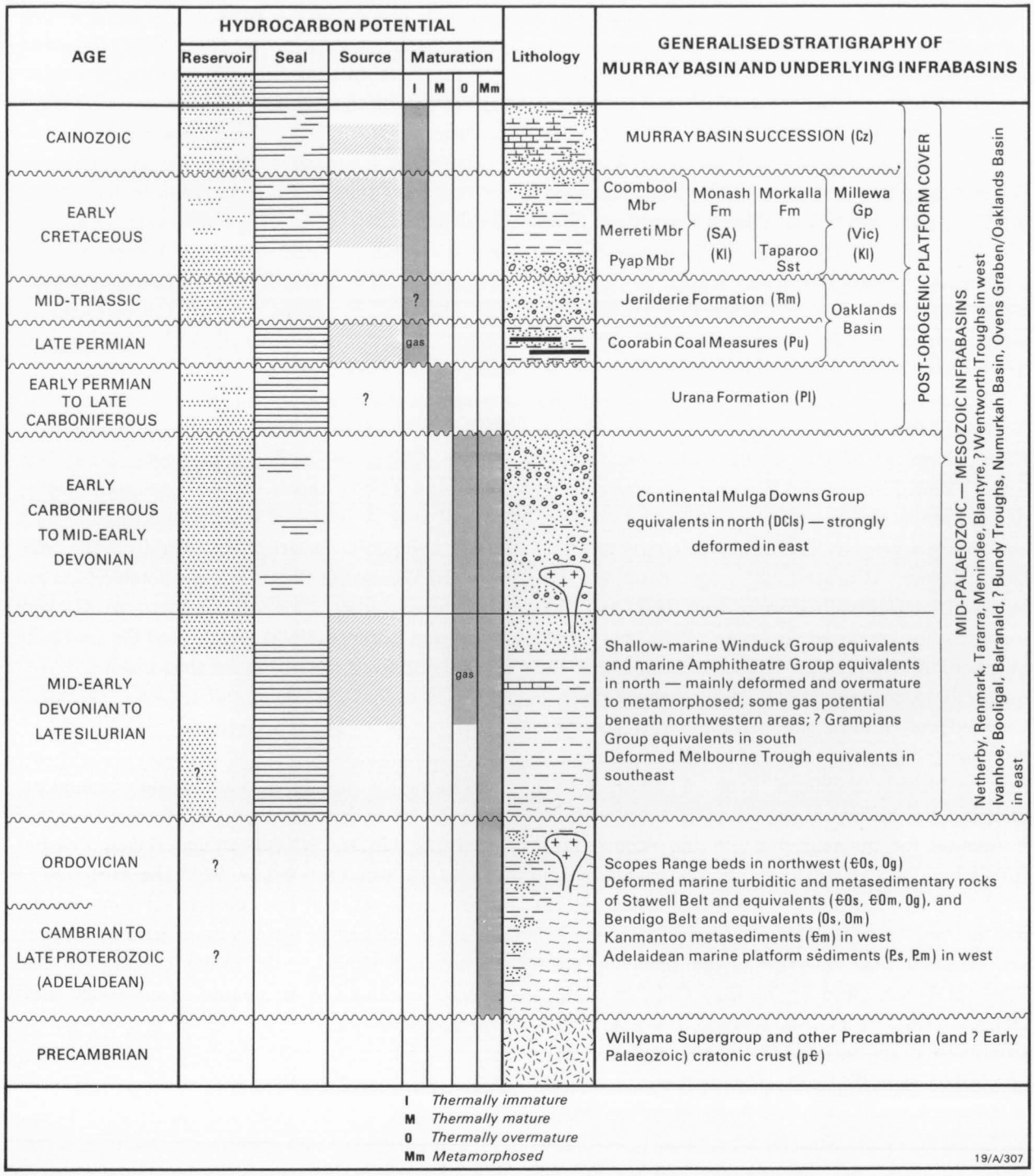


Fig. 174. Hydrocarbon potential of Murray Basin and underlying infrabasins.

Riverine Plain (Chapter 5; Fig. 23). The Renmark Trough was identified at an early stage and targeted for drilling. Elsewhere, however, many early bores were drilled into gravity anomalies which turned out to be shallow granites, and only a limited number of bores tested the deeper pre-Cainozoic sequences. As a result of this earlier work, a subsequent phase of exploration activity in the 1980's concentrated on the concealed troughs of the western Murray Basin. The potential of troughs, such as the Netherby Trough (see Chapter 5; Fig. 23; Orth, 1986), has not yet been fully investigated. Regional reviews of the exploration activity and hydrocarbon potential are presented in Bureau of Mineral Resources (1964), Bembrick (1974), Thornton (1974, 1976), Evans (1977), Brown & others (1982), Martin & Saxby (1984), Byrnes (1985), Sniffen (1985), and Campbell (1988). Petroleum exploration wells and major stratigraphic bores are listed on Table 45. Descriptions of the geology of the Upper Palaeozoic–Mesozoic in-

frabasins underlying the Cainozoic Murray Basin, and lithology logs of many of the exploration bores, are given in Chapter 5. Gravity, aeromagnetic and seismic exploration activity is discussed in Chapter 12, and surveys are listed on Tables 40, 41, and 42. Additional geological reports on petroleum exploration activity are in Ward (1944), Boutakoff & Sprigg (1953), Rose (1957, 1962b), Australian Oil & Gas (1956–62), Planet Exploration (1960–63), Landa Australian Oil (1961–62), North Australian Petroleum (1961–62), Overland Australian Oil (1961), Texam Oil (1961–62); Beaver Exploration (1973–76), Meyers (1974), Comserv (1979, 1981e, 1982b,c), Meekatharra Minerals (1981a,b), Blumer & Associates (1982), Esso Exploration (1982, 1986), McMaugh (1984e), Sprigg (1986), and Bligh Oil & Minerals (1989).

Potential hydrocarbon reservoirs and seals

The stratigraphy of the pre-Cainozoic infrabasins is summarised in Figure 25 and the intervals with potential reservoir rocks are shown on Figure 174.

The Lower Devonian (?Upper Silurian to mid-Lower Devonian) fine clastics of the Amphitheatre Group and its equivalents beneath the northwestern Murray Basin have unknown, but probably limited, reservoir potential. Evans (1977) suggested that hydrocarbons may occur within regressive Lower Devonian sandstone reservoirs of shallow-marine or deltaic facies, and may have been generated from, and sealed by, Lower Devonian marine shales now preserved in the concealed graben-like troughs beneath the northwestern Murray Basin. Although thin sands and minor carbonates occur within the sequence, they are usually well-cemented, hard and tight. Deformation decreases to the northwest, but most outcrops, and the limited available borehole data, suggest that the Lower Devonian has has undergone structural deformation and is quartz-veined and slickensided, and original porosity has largely been destroyed by deep burial. It therefore seems unlikely that porosity has been retained within the deeper parts of the troughs underlying the western Murray Basin; although some Lower Devonian (and ?older) rocks, which have remained at shallower depths flanking concealed basement ridges in northwestern areas may have retained porosity. It should be noted that the deeper sedimentary rocks have not yet been tested by drilling. Age-equivalent rocks to the south and east of the basin are strongly deformed and have no hydrocarbon potential.

In contrast to the above, the thick continental quartzose rocks of mid-Early Devonian to Early Carboniferous (mainly Late Devonian) age beneath northern areas (Mulga Downs Group and equivalents), contain good reservoirs in bores, such as Tararra No.1 (Boyd & Heisler, 1967) and Blantyre No.1 (Campe & Cundill, 1965), although locally the sequence is now well-cemented. The sequence could host hydrocarbons generated from underlying rocks. However, the limited available data indicates that the extremely thick potential reservoir sandstones have only thin intercalations of shales, and suitable seal rocks to trap hydrocarbons within the sequence have not yet been identified. In contrat, the overlying Permian succession provides an excellent seal at the top of the Devonian sandstone unit, but was possibly not present at the probable time of petroleum generation in the underlying Lower Devonian succession (Brown & others, 1982).

In several infrabasins, sandstone within the Upper Carboniferous–Lower Permian Urana Formation and equivalents locally have retained good porosity (Thornton, 1974; e.g. in Monash No.1 – Walter, 1965, and Berri North No.1 – Laws & Heisler, 1967). The Lower Permian sediments therefore have some reservoir potential, but it should be noted that much of the glacio-marine unit (O'Brien, 1986) is fine-grained, and consists of chemically and texturally immature lithic grains, which breakdown and destroy porosity. Where present, the unit has the potential to form an excellent seal, both at the top of the underlying Devonian sandstone, and around the minor intra-formational sandstone beds. The Upper Permian Coorabin Coal Measures and mid-Triassic Jerilderie Formation, confined to the Oaklands Basin region beneath the southeastern Riverine Plain, have fluvial channel sands with excellent porosity. These, however, occur at shallow depths and may have been flushed with relatively modern groundwater. In the Renmark Trough and adjacent areas, the quartzose sands of the Pyap Member of the Monash Formation have been found to have excellent reservoir characteristics, with porosities of up to 40% (Thornton, 1974; e.g. Berri North No.1 – Laws & Heisler, 1967, Sunset No.1 – Derrington & Anderson, 1970), but sands within the overlying Merreti and Coombool Members have a volcanolithic component and are poorer reservoirs, but provide a seal above the Pyap Member.

Several units with excellent porosity and permeability, as well as a number of impermeable rocks, occur within the Cainozoic succession. However, they are unlikely to contain hydrocarbons. Radke (1987) reported the presence of bituminous-like resinous or-

TABLE 45. PETROLEUM EXPLORATION WELLS AND DEEP STRATIGRAPHIC BORES (1 of 2)

Well/Bore	*Latitude Longitude*	*Year*	*T.D.*	*Company*	*Reference*
Avery No.1	33 06 14 S 141 27 14 E	1986	605	Claremont Petroleum	Gorter (1986a)
Balranald No.1	34 39 20 S 143 29 32 E	1962	403	Woodside	Benbow (1962)
Berangabah No.1	32 17 30 S 144 28 00 E	1967	436	Texam Oil Corp.	Ranneft (1968)
Berri North No.1	34 12 17 S 140 38 06 E	1967	945	Beach Petroleum	Laws & Heisler (1967)
Berri South No.1	34 22 03 S 140 38 01 E	1966	664	Beach Petroleum	Gausden & Watts (1966)
Blackgate No.1	32 05 18 S 142 37 12 E	1980	1932	Comserv (799)	Sniffen (1985)
Blantyre No.1	32 09 15 S 143 09 40 E	1965	2289	Mideastern Oil	Campe & Cundill (1965)
Booligal No.2	33 35 15 S 144 56 30 E	1970	811	N.S.W. Oil & Gas	Haskell (1970a)
Bundy No.1	35 03 00 S 144 31 18 E	1962	419	Woodside	Shiels (1962)
Canopus No.1	33 23 03 S 140 40 51 E	1952	290	S.A. Dept. Mines	Ludbrook (1961a)
Canopus No.2	33 19 42 S 140 42 25 E	1953	306	S.A. Dept. Mines	Ludbrook (1961a)
Company Bore	34 07 18 S 140 41 08 E	1910	550	Loxton Farm Co.	Thornton (1974)
Cooltong No.1	34 06 42 S 140 30 19 E	1987/88	1329	International Mining	Archer (1988)
Coonalpyn No.1	35 40 00 S 140 00 00 E	1958	208	Murray Basin Oil Synd.	Thornton (1974)
Dolmoreve No.1	33 30 00 S 144 00 06 E	1967	471	Texam Oil Corp.	Ranneft (1967)
Donna No.1	35 29 15 S 138 55 14 E	1964	701	Geoil Ltd.	Thornton (1974)
Echuca North	36 07 33 S 144 45 10 E	?	216	Vic. Dept. Mines	Lawrence (1975)
Ennisvale No.1	33 18 15 S 141 11 23 E	1983	1231	Esso Exploration	Lindsay (1983) & McMaugh (1984a)
Gunamalary No.2	35 19 56 S 141 11 31 E	1986	718	D.I.T.R.	Orth (1986)
Hay No.1	34 54 23 S 144 50 29 E	1970	350	N.S.W. Oil & Gas	Haskell (1970b)
Holey Box No.1	33 05 00 S 144 31 00 E	1967	349	North Star Oil	Texam Oil Corp. (1967)
Ironstone Tk.No.1	33 07 39 S 141 23 05 E	1986	605	Claremont	Gorter (1986b)
Ivanhoe No.1	32 54 11 S 144 17 51 E	1963	666	North Star Oil	Brundall (1964)
Jerilderie No.1	35 15 00 S 145 58 00 E	1962	1329	Australian Oil & Gas	Wright & Stuntz (1963)
Keith No.1	36 10 00 S 140 45 00 E	1958	292	Murray Basin Oil Synd.	Thornton (1974)
Killendoo No.1	34 41 01 S 145 04 09 E	1964	757	Amalgamated Pet. Expl.	Haites & Stewart (1964)
Kopi Plain No.1	33 13 49 S 141 16 07 E	1986	1547	Claremont	Gorter (1986c)
Lake Victoria No.1	34 03 15 S 141 20 53 E	1964	754	Australian Oil & Gas	Grasso (1964)
Loxton No.1	34 34 00 S 140 39 00 E	1956	488	Australian Oil & Gas	Ludbrook (1956)
Loxton No.2	34 34 00 S 140 35 49 E	1963	550	Beach Petroleum	Laws (1963)
Mildura West No.1	34 32 31 S 141 24 26 E	1983	428	S.A.O.G.C.	S.A. Oil & Gas (1983a) & Suttill (1983a)
Mildura West No.2	34 32 29 S 141 17 05 E	1983	597	S.A.O.G.C.	S.A. Oil & Gas(1983b) & Suttill (1983b)
Monash No.1	34 12 00 S 140 29 57 E	1964	1050	Beach Petroleum	Walter (1965)
Morkalla No.1	34 22 25 S 141 09 55 E	1970	783	Assoc. Austr. Oilfields	Derrington & Anderson (1970)
Mount Emu No.1	32 19 56 S 143 32 33 E	1970	1450	Planet Oil Explor. Co.	Haskell & Wiltshire (1970)
Nadda No.1	34 38 05 S 140 53 45 E	1970	1041	Assoc. Austr. Oilfields	Derrington & Anderson (1970)
Nambucurra No.1	33 19 38 S 142 50 09 E	1970	263	N.S.W. Oil & Gas Co.	Haskell (1970b)
Naracoorte Bore	36 57 29 S 140 44 19 E	1950	150	S.A. Dept. Mines	O'Driscoll (1960)
North Renmark No.1	34 07 00 S 140 41 00 E	1962	1225	Australian Oil Corp	Grasso (1963)
Nulla Nulla No.1	33 37 36 S 141 01 19 E	1983	1119	Esso Exploration	Lindsay (1984) & McMaugh (1984b)
Oakvale No.1	32 59 03 S 142 50 09 E	1981	176	S.A. Dept. Min. & Energy	Lindsay (1983a) & Forbes (1984)
Olney No.1	34 05 55 S 141 01 12 E	1964	614	Vic. Dept. Mines	Lawrence (1975)
Overland Corner No.1	34 04 06 S 140 18 03 E	1984	645	International Mining	Furr (1984)
Pamamaroo No.1	32 10 22 S 142 29 42 E	1983	798	Esso Exploration	Moreton (1983) & McMaugh (1984c)
Piangil West No.2	35 03 10 S 143 13 07 E	1987	380	D.I.T.R.	Radke (1987) & Brown & Radke (1989)
Pinnaroo No.1	35 17 00 S 140 35 00 E	1958	390	Murray Basin Oil Synd.	O'Driscoll (1960)
Popiltah No.1	33 22 39 S 141 41 31 E	1983	1003	Esso Exploration	Archibold (1984) & McMaugh (1984d)
Robinvale No.1	34 49 14 S 142 41 04 E	1983	246	S.A.O.G.C.	S.A. Oil & Gas (1983c)
Shaugh Bore	35 57 10 S 140 46 54 E	1946	283	S.A. Dept. Mines	Thornton (1974)
Sunset No.1	34 16 30 S 141 06 25 E	1970	1001	Assoc.. Aust. Oilfields	Derrington & Anderson(1970)

TABLE 45. ctd. (2 of 2)

Well/Bore	*Latitude Longitude*	*Year*	*T.D.*	*Company*	*Reference*
Tailem Bend No.1	35 11 17 S 139 31 15 E	1956	81	Murray Basin Oil Synd.	Thornton (1974)
Tararra No.1	33 20 12 S 141 15 49 E	1967	1935	Australian Oil & Gas	Boyd & Heisler (1967)
Umalee No.1	32 48 31 S 144 03 27 E	1962	176	N.S.W. Dept. Min. Res.	Yoo (1981b)
Urana No.2	35 16 39 S 146 00 55 E	1981	675	Amalgamated Petrol.	Amalg. Petrol. (1962) & Payne (1962)
Waikerie 27W/28W	34 11 34 S 139 58 48 E	1965	383	S.A. Dept. Mines	Lindsay & Bonnett (1973)
Waikerie 2W	34 12 54 S 139 57 48 E	1969		S.A. Dept. Mines	Lindsay & Bonnett (1973)
Wentworth No.1	33 48 45 S 141 58 15 E	1961	634	Australian Oil & Gas	Rose (1962a)
Yellangip No.1	36 07 43 S 142 24 52 E	?	227	Vic. Dept. Mines	Lawrence (1975)

ganic material of unknown origin, infilling pore space within the Geera Clay in Piangil West-2 borehole. The resin is possibly a residue of a migrating oil sourced from pre-Cainozoic sediments. However, the resin is similar in composition to derivatives from wood or tree sap and could also have been sourced from the adjacent Renmark Group, or from within the Geera Clay. Macphail (1988a,b) subsequently noted the presence of swollen spore-pollen, in Geera Clay in Piangil West-2 and Woodlands-1 boreholes, which he suggested may indicate the presence of hydrocarbons (Macphail & Truswell, 1989).

Hydrocarbon source rock potential and maturation

The hydrocarbon source potential and maturity of the various stratigraphic sequences underlying the Murray Basin are summarised on Figure 174. The degree of structural deformation of sedimentary rocks older than Late Silurian indicate that these can be eliminated as potential source rocks. Alliance Oil Development (1968d), for example, drilled 12 shallow bores in the Scopes Range area to test the source rock potential of Cambro-Ordovician basement rocks. Minor weakly metamorphosed shales were encountered, and the total organic carbon content was found to be less than 0.4%. Bembrick (1976a) and Byrnes (1985) suggested that relatively unmetamorphosed Lower Palaeozoic marine sediments with source potential may underlie the Bancannia Trough (see Fig. 22; Bembrick, 1976b) and other infrabasins concealed beneath the northern Murray Basin, but such rocks have not yet been encountered by exploration wells, and Evans (1977) and Brown & others (1982) considered the Lower Palaeozoic rocks to have negligible remaining oil source potential, due to deep burial beneath the Devonian succession.

The degree of induration of the folded Upper Silurian–Lower Devonian rocks east and south of the Murray Basin suggests that any source potential is restricted to the troughs underlying the western Murray Basin. Fine-grained Lower Devonian marine sedimentary rocks are only rarely exposed, and have only been encountered in four exploration wells and one stratigraphic bore. Mount Emu No.1 (Haskell & Wiltshire, 1970) penetrated a sequence lacking in fine-grained rocks with preserved source potential. Texam Berangabah No.1 (Ranneft, 1968), located on the southeastern flank of the Lake Poopelloe Trough (Fig. 22), intersected shaly siltstone with up to 6% carbonaceous matter, and spores and acritarchs were not excessively carbonised (Ranneft, 1968). A core from Poopelloe Lake No.1 (Fig. 22), however, showed mineral and fabric alteration associated with deep burial (Wiltshire, 1970), implying thermal destruction of source potential, and it seems likely that source rocks at depth elsewhere in the troughs have been subject to similar excessive maturation (Evans, 1977), and hence potentially mature oil source rocks are only likely to be preserved at relatively shallow depths on the flanks of troughs.

Of a total of 14 core samples from BMR Ivanhoe No.1 (Passmore, 1981; Fig. 18) analysed, three returned values of 0.46%, 0.81% and 0.98% total organic carbon (TOC; Brown & others, 1982). A plot of total hydrocarbons (SATS plus AROM) against TOC indicated that most samples were lean to barren. The sediments are indurated, but show no signs of incipient metamorphism, although some of the shale laminae were slickensided and fracturing is common. Estimates of colour alteration of conodont elements (Jones & others, 1981) indicated that the sediments had been subjected to temperatures no greater than 140°C, placing the sediments at the upper temperature end of the oil window, and indicating the sequence to be thermally mature to overmature. The finely disseminated organic matter consists mostly of herbaceous and woody debris,

lacking in algal material (E.M. Truswell, pers. comm., in Brown & others, 1982) and therefore may have been a source of gas rather than liquid hydrocarbons. The presence of spores with medium to dark colouration suggest that these are equivalent to a thermal alteration index of 4 – again indicating overmaturity. This overmaturity, in combination with indicators of fair to lean source potential, suggests that the overmature rocks may have had greater oil potential in the past. In general, the Lower Devonian marine sequence currently has a low organic carbon content, is probably gas prone, is thermally mature to overmature within the troughs, and is downgraded as a potential source rock (Brown & others, 1982). Outcrops of the shallow-marine sandstones of the Winduck Group that occur towards the top of the Lower Devonian marine sequence contain little or no carbonaceous material and only minor intercalated shale, and are thus believed to have little or no source rock potential. Similarly, the thick, coarse-grained fluviatile rocks of Mid-Lower Devonian to Lower Carboniferous age appear to have only limited source potential, owing to their continental affinities and the red-bed character of associated fine clastics. However, if suitable traps occur within the sands, they could contain hydrocarbins generated from underlying sequences.

Maturation indicators (mainly vitrinite reflectance data) suggest that the Upper Carboniferous to Lower Permian sequence, as well as the Upper Permian in the Oaklands Basin, ranges from immature to marginally mature (within the oil generation window). Unfortunately, the available total organic carbon and other analyses suggest that, despite favourable maturation, the sequence has poor source potential, with the only high values being obtained from atypical carbonaceous intervals. It should be noted, however, that only a very limited number of spot samples have been tested, and regional trends have not been established. Minor indication of hydrocarbons came from Jerilderie No.1, which encountered a small gas show (Wright & Stuntz, 1963), and from Barmah No. 34 bore which encountered an oil show in a 2 m thick Upper Permian sand (Brinkly & others, 1989; M.A. Reid, Rural Water Commission of Victoria, personal communication, 1989).

Within the Lower Cretaceous sequence, the sandstone of the basal Pyap Member of the Monash Formation contains intercalated coal, but is generally lacking in fine-grained sediment. The overlying Merreti and Coombool Members of the Monash Formation include carbonaceous marine shales which are potential source rocks; analyses of shales, from a number of exploration wells, have revealed high TOC values, although, in many cases these relate to the high carbonaceous content of the sediments. Few maturation tests have been undertaken, but the available vitrinite reflection data indicate generally low reflectance, suggesting that the Lower Cretaceous succession is thermally immature for the generation of liquid hydrocarbons, but may have potential for the generation of low temperature gas. The overlying Cainozoic succession is similarly thermally immature.

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APPENDIX 1

Co-ordinates of geographic names mentioned in text

APPENDIX 1 – CO-ORDINATES OF GEOGRAPHIC NAMES (page 1 of 4)

Place	*Map Sheet*	*Latitude*	*Longitude*
Agnes Lake	OUYEN	35 10 00 S	144 00 00 E
Aire River	COLAC	38 42 00 S	143 29 00 E
Alawoona	RENMARK	34 44 00 S	140 31 00 E
Albacutya Lake	OUYEN	35 45 00 S	141 58 00 E
Albert Lake	BARKER	35 38 00 S	139 18 00 E
Albury	WANGARATTA	35 05 00 S	146 56 00 E
Alexandrina Lake	BARKER	35 25 00 S	139 10 00 E
Angas River	BARKER	35 20 00 S	139 00 00 E
Arumpo	POONCARIE	33 48 00 S	142 53 00 E
Avoca River	SWAN HILL/ST.ARNAUD	35 46 00 S	143 37 00 E
Avon River	ST.ARNAUD	36 35 00 S	142 50 00 E
Axedale	BENDIGO	36 47 00 S	144 30 00 E
Ballarat	BALLARAT	37 34 00 S	143 51 00 E
Balranald	BALRANALD	34 38 00 S	143 34 00 E
Barmah	BENDIGO	36 01 00 S	144 57 00 E
Barmah State Forest	DENILIQUIN	35 55 00 S	144 58 00 E
Barmera	RENMARK	34 15 00 S	140 28 00 E
Barrier Range	BROKEN HILL	31 41 00 S	141 24 00 E
Barwo	BENDIGO	36 02 00 S	145 10 00 E
Beachport	PENOLA	37 29 00 S	140 00 00 E
Bendigo	BENDIGO	36 46 00 S	144 17 00 E
Bendigo (NSW)	JERILDERIE	35 14 00 S	145 40 00 E
Benjeroop	SWAN HILL	35 29 00 S	143 50 00 E
Berri	RENMARK	34 17 00 S	140 36 00 E
Big Desert	OUYEN	35 26 00 S	141 16 00 E
Binnie Lookout	PINNAROO	35 41 00 S	139 39 00 E
Black Range	HAMILTON	37 10 00 S	142 04 00 E
Blanchetown	RENMARK	34 21 00 S	139 37 00 E
Boga Lake	SWAN HILL	35 27 00 S	143 38 00 E
Boinka	OUYEN	35 12 00 S	141 36 00 E
Booligal	BOOLIGAL	33 52 00 S	144 53 00 E
Bootingee	MENINDEE	32 29 00 S	142 23 00 E
Bordertown	NARACOORTE	36 18 00 S	140 46 00 E
Bower	ADELAIDE	34 08 00 S	139 21 00 E
Bremer River	BARKER	35 23 00 S	139 03 00 E
Bridgewater	PORTLAND	38 24 00 S	141 25 00 E
Bridgewater (Vic)	ST.ARNAUD	36 36 00 S	143 57 00 E
Broken Hill	BROKEN HILL	31 58 00 S	141 27 00 E
Buccleuch	PINNAROO	35 20 00 S	139 53 00 E
Bullatale Creek	DENILIQUIN	35 40 00 S	144 59 00 E
Buloke Lake	ST.ARNAUD	36 16 00 S	142 58 00 E
Bungunnia	CHOWILLA	33 56 00 S	139 42 00 E
Buntigoola Tank	MENINDEE	32 49 00 S	142 16 00 E
Bunyip Reach	RENMARK	34 01 00 S	140 53 00 E
Burra Creek	BURRA/CHOWILLA	33 43 00 S	138 57 00 E
Cadell	RENMARK	34 03 00 S	139 46 00 E
Calivil	BENDIGO	36 18 00 S	144 05 00 E
Campaspe River	BENDIGO	36 14 00 S	144 45 00 E
Cape Bridgewater	PORTLAND	38 23 00 S	141 24 00 E
Cape Jervis	BARKER	35 36 00 S	138 06 00 E
Casterton	HAMILTON	37 36 00 S	141 24 00 E
Cawndilla Lake	MENINDEE	32 29 00 S	142 14 00 E
Chandos	PINNAROO	35 17 00 S	140 47 00 E
Chibnalwood Lakes	POONCARIE	35 53 00 S	143 01 00 E
Chowilla Creek	CHOWILLA	33 59 00 S	140 52 00 E
Cobram	JERILDERIE	35 55 00 S	145 39 00 E
Cohuna	DENILIQUIN	35 49 00 S	144 13 00 E
Coliban River	BALLARAT/BENDIGO	36 58 00 S	144 29 00 E
Compton	PENOLA	37 48 00 S	140 44 00 E
Cooke Plains	PINNAROO	35 23 00 S	139 34 00 E
Coomandook	PINNAROO	35 28 00 S	139 42 00 E
Coombool Swamp	CHOWILLA	33 54 00 S	140 53 00 E
Coonalpyn	PINNAROO	35 42 00 S	139 51 00 E
Coonambidgal Creek	DENILIQUIN	35 30 00 S	144 57 00 E
Coorabin	JERILDERIE	35 30 00 S	146 13 00 E
Coorong	BARKER/NARACOORTE	35 47 00 S	139 17 00 E
Danyo	OUYEN	35 16 00 S	141 17 00 E
Darling Anabranch	ANABRANCH/MENINDEE	34 00 00 S	141 49 00 E
Darling River	ANABRANCH/MENINDEE	32 30 00 S	142 23 00 E
Darlington Point	NARRANDERA	34 34 00 S	146 00 00 E
Darnick Range	MANARA	32 53 00 S	143 28 00 E
Deniliquin	DENILIQUIN	35 32 00 S	144 57 00 E
Diapur	HORSHAM	36 19 00 S	141 28 00 E
Dimboola	HORSHAM	36 27 00 S	142 02 00 E
Duddo	OUYEN	35 09 00 S	141 16 00 E
Dundas (Mt.)	HAMILTON	37 28 00 S	141 55 00 E
E. Avenue Range	NARACOORTE	36 45 00 S	140 11 00 E
Echuca	BENDIGO	36 08 00 S	144 45 00 E
Edenhope	HAMILTON	37 02 00 S	141 17 00 E
Edward River	DENILIQUIN	35 21 00 S	144 37 00 E
Elwomple	PINNAROO	35 17 00 S	139 34 00 E

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Place	*Map Sheet*	*Latitude*	*Longitude*
Enfield	ADELAIDE	34 52 00 S	138 35 00 E
Eppalock Lake	BENDIGO	36 52 00 S	144 34 00 E
Euroa	WANGARATTA	36 45 00 S	143 34 00 E
Finniss	BARKER	35 23 00 S	138 50 00 E
Fleurieu Peninsula	BARKER	35 34 00 S	138 20 00 E
Frances	NARACOORTE	36 43 00 S	140 57 00 E
Garnpung	POONCARIE	33 30 00 S	143 06 00 E
Glenelg River	HAMILTON	37 17 00 S	141 16 00 E
Gol Gol	POONCARIE	33 30 00 S	143 19 00 E
Gol Gol Lake	MILDURA	34 08 00 S	142 14 00 E
Goulburn River	BENDIGO	36 10 00 S	145 05 00 E
Grampians Range	HAMILTON	37 00 00 S	142 27 00 E
Great Cumbung Swamp	HAY	34 17 00 S	144 02 00 E
Gredgwin	SWAN HILL	35 58 00 S	143 37 00 E
Green Gully	DENILIQUIN	35 56 00 S	144 47 00 E
Greenhill Creek	ST.ARNAUD	35 56 00 S	143 38 00 E
Griffith	NARRANDERA	34 17 00 S	146 02 00 E
Hamilton	HAMILTON	37 45 00 S	142 02 00 E
Hartley	BARKER	35 12 00 S	139 01 00 E
Hatfield	POONCARIE	33 52 00 S	143 44 00 E
Hay	HAY	34 30 00 S	144 51 00 E
Heathcote	BENDIGO	36 55 00 S	144 42 00 E
Hillston	CARGELLIGO	33 29 00 S	145 32 00 E
Hindmarsh Lake	HORSHAM	36 04 00 S	141 55 00 E
Horsham	HORSHAM	36 43 00 S	142 12 00 E
Ivanhoe	IVANHOE	32 54 00 S	144 18 00 E
Jerilderie	JERILDERIE	35 22 00 S	145 43 00 E
Kadnook Creek	HAMILTON	37 12 00 S	141 21 00 E
Kaniva	HORSHAM	36 23 00 S	141 15 00 E
Kanyapella	BENDIGO	36 10 00 S	144 47 00 E
Karoonda	PINNAROO	35 06 00 S	139 54 00 E
Karte	PINNAROO	35 04 00 S	140 42 00 E
Katandra	WANGARATTA	36 15 00 S	145 35 00 E
Keith	NARACOORTE	36 06 00 S	140 21 00 E
Kerang	SWAN HILL	35 44 00 S	143 55 00 E
Ki Ki	PINNAROO	35 34 00 S	139 48 00 E
Kialla	BENDIGO	36 28 00 S	145 25 00 E
Kiewa River	WANGARATTA	36 10 00 S	146 59 00 E
Kinchega	MENINDEE	32 29 00 S	142 21 00 E
King River	WANGARATTA	36 28 00 S	146 22 00 E
Kingston	NARACOORTE	36 50 00 S	139 51 00 E
Kingston-on-Murray	RENMARK	34 14 00 S	140 21 00 E
Kotupna	BENDIGO	36 09 00 S	145 08 00 E
Kow Swamp	DENILIQUIN	35 57 00 S	144 17 00 E
Kyalite	BALRANALD	34 57 00 S	143 29 00 E
Laceby	WANGARATTA	36 19 00 S	146 18 00 E
Lachlan River	CARGELLIGO/BOOLIGAL	33 55 00 S	144 50 00 E
Lah	HORSHAM	36 08 00 S	142 25 00 E
Lake Agnes	OUYEN	35 10 00 S	144 00 00 E
Lake Albacutya	OUYEN	35 45 00 S	141 58 00 E
Lake Albert	BARKER	35 38 00 S	139 18 00 E
Lake Alexandrina	BARKER	35 25 00 S	139 10 00 E
Lake Arumpo	POONCARIE	33 49 00 S	142 55 00 E
Lake Boga	SWAN HILL	35 27 00 S	143 38 00 E
Lake Buloke	ST.ARNAUD	36 16 00 S	142 58 00 E
Lake Cargelligo	CARGELLIGO	33 18 00 S	146 22 00 E
Lake Cawndilla	MENINDEE	32 29 00 S	142 14 00 E
Lake Chibnalwood	POONCARIE	35 53 00 S	143 01 00 E
Lake Eppalock	BENDIGO	36 52 00 S	144 34 00 E
Lake Garnpung	POONCARIE	33 26 00 S	143 10 00 E
Lake Gol Gol	MILDURA	34 08 00 S	142 14 00 E
Lake Hindmarsh	HORSHAM	36 04 00 S	141 55 00 E
Lake Kanyapella	BENDIGO	36 10 00 S	144 54 00 E
Lake Menindee	MENINDEE	32 20 00 S	142 20 00 E
Lake Merreti	RENMARK/CHOWILLA	34 01 00 S	140 46 00 E
Lake Mungo	POONCARIE	33 39 00 S	143 00 00 E
Lake Popiltah	ANABRANCH	33 08 00 S	141 43 00 E
Lake Popio	ANABRANCH	33 09 00 S	141 51 00 E
Lake Tandou	MENINDEE	32 38 00 S	142 05 00 E
Lake Travellers	ANABRANCH	33 18 00 S	142 00 00 E
Lake Tyrrell	SWAN HILL	35 23 00 S	142 50 00 E
Lake Victoria	ANABRANCH/MILDURA	33 58 00 S	141 16 00 E
Lawloit	HORSHAM	36 25 00 S	141 28 00 E
Leaghur	SWAN HILL	35 58 00 S	143 56 00 E
Leeton	NARRANDERA	34 33 00 S	146 24 00 E
Linga	OUYEN	35 10 00 S	141 42 00 E
Little Desert	HORSHAM	36 35 00 S	141 45 00 E
Loddon River	ST.ARNAUD/SWAN HILL	36 30 00 S	143 59 00 E
Loveday	RENMARK	34 17 00 S	140 25 00 E
Lowan Hmstd.	PENOLA	37 33 00 S	140 46 00 E

(page 3 of 4)

Place	*Map Sheet*	*Latitude*	*Longitude*
Loxton	RENMARK	34 27 00 S	140 34 00 E
Mallee Cliffs Ntnl. Pk.	BALRANALD/MILDURA	34 13 00 S	142 37 00 E
Manangatang	SWAN HILL	35 03 00 S	142 53 00 E
Manara Hills	MANARA	32 32 00 S	143 53 00 E
Manfred	POONCARIE	33 19 00 S	143 46 00 E
Manfred Range	POONCARIE	33 12 00 S	143 29 00 E
Mannum	ADELAIDE	34 55 00 S	139 18 00 E
Marmon Jabuk Range	PINNAROO	35 22 00 S	140 00 00 E
Marmon Jabuk Scarp	PINNAROO	35 22 00 S	140 00 00 E
Marne River	ADELAIDE/RENMARK	34 40 00 S	139 19 00 E
Mayrung	DENILIQUIN	35 28 00 S	145 18 00 E
Menindee	MENINDEE	32 24 00 S	142 25 00 E
Menindee Lake	MENINDEE	32 20 00 S	142 20 00 E
Merbein	MILDURA	34 10 00 S	142 04 00 E
Meretti Lake	RENMARK/CHOWILLA	34 01 00 S	140 46 00 E
Mildura	MILDURA	34 11 00 S	142 10 00 E
Millewa	RENMARK	34 01 00 S	140 58 00 E
Miralie	SWAN HILL	35 07 00 S	143 19 00 E
Mitta Mitta River	TALLANGATA	36 32 00 S	147 27 00 E
Monarto	BARKER	35 03 00 S	139 07 00 E
Monash	RENMARK	34 14 00 S	140 33 00 E
Monoman Creek	CHOWILLA	35 58 00 S	140 52 00 E
Moorlands	PINNAROO	35 18 00 S	139 39 00 E
Moorna	MILDURA	34 08 00 S	141 36 00 E
Morgan	RENMARK	34 02 00 S	139 40 00 E
Morkalla	MILDURA	34 22 00 S	141 10 00 E
Mount Gambier	PENOLA	37 50 00 S	140 47 00 E
Mount Lofty Ranges	ADELAIDE	34 59 00 S	138 43 00 E
Mount Muirhead	PENOLA	37 34 00 S	140 24 00 E
Mount Napier	HAMILTON	37 54 00 S	142 04 00 E
Mount Rouse	HAMILTON	37 53 00 S	142 18 00 E
Mungo	POONCARIE	33 44 00 S	143 01 00 E
Murray Bridge	BARKER	35 07 00 S	139 16 00 E
Murrayville	OUYEN	35 16 00 S	141 11 00 E
Murrumbidgee River	NARRANDERA/HAY	34 31 00 S	144 22 00 E
Nanya	ANABRANCH	33 13 00 S	141 19 00 E
Naracoorte	NARACOORTE	36 58 00 S	140 45 00 E
Narrancoolambund Lagoon	NARRANDERA	34 33 00 S	145 59 00 E
Narrandera	NARRANDERA	34 45 00 S	146 33 00 E
Native Dog Creek	DENILIQUIN	35 48 00 S	145 24 00 E
Neckarboo	IVANHOE	32 04 00 S	144 36 00 E
Neckarboo Range	IVANHOE	32 06 00 S	144 26 00 E
Netherby	HORSHAM	36 07 00 S	141 39 00 E
Nhill	HORSHAM	36 20 00 S	141 39 00 E
Noora	RENMARK	34 26 00 S	140 52 00 E
North West Bend	RENMARK	34 01 00 S	139 42 00 E
Nulla Nulla	ANABRANCH	33 48 00 S	141 19 00 E
Numurkah	BENDIGO	36 06 00 S	145 26 00 E
Nyah	SWAN HILL	35 11 00 S	143 23 00 E
Nyah West	SWAN HILL	35 11 00 S	143 21 00 E
Oakland	JERILDERIE	35 33 00 S	146 10 00 E
Oakvale	OLARY	32 59 00 S	140 47 00 E
Ovens River	WANGARATTA	36 12 00 S	146 16 00 E
Overland Corner	RENMARK	34 09 00 S	140 20 00 E
Packers Lake	MENINDEE	32 43 00 S	142 10 00 E
Padthaway	NARACOORTE	36 36 00 S	140 29 00 E
Parilla	PINNAROO	35 18 00 S	140 40 00 E
Paringa	RENMARK	34 11 00 S	140 47 00 E
Pata	RENMARK	34 34 00 S	140 32 00 E
Peake	PINNAROO	35 22 00 S	139 57 00 E
Piangil	SWAN HILL	35 03 00 S	143 18 00 E
Pine Camp	ANABRANCH	33 46 00 S	141 03 00 E
Pine Lodge	WANGARATTA	36 22 00 S	145 32 00 E
Pink Lakes	OUYEN	35 03 00 S	141 44 00 E
Pinnaroo	PINNAROO	35 16 00 S	140 55 00 E
Pooncarie	POONCARIE	33 24 00 S	142 34 00 E
Pooraka	ADELAIDE	34 50 00 S	138 38 00 E
Popiltah Lake	ANABRANCH	33 08 00 S	141 43 00 E
Popio Lake	ANABRANCH	33 09 00 S	141 51 00 E
Port Campbell	COLAC	38 37 00 S	143 00 00 E
Portland	PORTLAND	38 21 00 S	141 36 00 E
Powlett Plains	ST.ARNAUD	36 27 00 S	143 54 00 E
Pyap Lagoon	RENMARK	34 24 00 S	140 27 00 E
Quambatook	SWAN HILL	35 51 00 S	143 31 00 E
Quiamong	DENILIQUIN	35 18 00 S	145 12 00 E
Raak Plains	MILDURA	34 40 00 S	142 00 00 E
Ramco	RENMARK	34 10 00 S	139 57 00 E
Red Bluff	?OUYEN	35 53 00 S	141 03 00 E
Renmark	RENMARK	34 10 00 S	140 45 00 E
Robe	PENOLA	37 10 00 S	139 45 00 E
Robinvale	BALRANALD	34 35 00 S	142 46 00 E

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Place	*Map Sheet*	*Latitude*	*Longitude*
Rufus River	MILDURA	34 03 00 S	141 16 00 E
Scopes Range	BROKEN HILL	31 51 00 S	142 43 00 E
Shepparton	BENDIGO	36 23 00 S	145 24 00 E
South Flinders Ranges	ORRORO0	32 08 00 S	138 46 00 E
Speewa	SWAN HILL	35 14 00 S	143 31 00 E
St.Kilda	ADELAIDE	34 44 00 S	138 32 00 E
Stavely	BALLARAT	37 36 00 S	142 38 00 E
Stawell	BALLARAT	37 03 00 S	142 47 00 E
Strathbogie Range	WANGARATTA	36 56 00 S	145 38 00 E
Sunset Country/Desert	MILDURA/OUYEN	35 00 00 S	141 47 00 E
Swan Hill	SWAN HILL	35 20 00 S	143 33 00 E
Tailem Bend	BARKER	35 15 00 S	139 28 00 E
Talgarry	ANABRANCH	33 56 00 S	141 25 00 E
Tallygaroopna	BENDIGO	36 14 00 S	145 26 00 E
Talyawalka Creek	MANARA	32 18 00 S	142 59 00 E
Tandou Creek	MENINDEE	32 38 00 S	142 14 00 E
Tandou Lake	MENINDEE	32 38 00 S	142 05 00 E
Taparoo	MILDURA	34 19 00 S	141 02 00 E
Tararra	ANABRANCH	33 17 00 S	141 12 00 E
Tocumwal	JERILDERIE	35 49 00 S	154 34 00 E
Tooleybuc	SWAN HILL	35 02 00 S	143 29 00 E
Torrumbarry	BENDIGO	36 02 00 S	144 31 00 E
Tragowel	SWAN HILL	35 51 00 S	143 59 00 E
Travellers Lake	ANABRANCH	33 18 00 S	142 00 00 E
Tyntynder	SWAN HILL	35 15 00 S	143 34 00 E
Tyrrell Creek	SWAN HILL	35 48 00 S	143 12 00 E
Urana	JERILDERIE	35 20 00 S	146 16 00 E
Waaia	BENDIGO	36 03 00 S	145 20 00 E
Waikerie	RENMARK	34 11 00 S	139 59 00 E
Wakool	DENILIQUIN	35 28 00 S	144 24 00 E
Walls of China	POONCARIE	33 45 00 S	143 08 00 E
Wanbi	RENMARK	34 46 00 S	140 19 00 E
Wandella Creek	SWAN HILL	35 48 00 S	143 50 00 E
Wanganella	DENILIQUIN	35 13 00 S	144 49 00 E
Wangaratta	WANGARATTA	36 21 00 S	146 19 00 E
Wedderburn	ST.ARNAUD	36 26 00 S	143 37 00 E
Wellington	BARKER	35 20 00 S	139 23 00 E
Wentworth	MILDURA	34 06 00 S	141 55 00 E
West Naracooorte Range	NARACOORTE	36 45 00 S	140 38 00 E
Whyalla	WHYALLA	33 02 00 S	137 35 00 E
Widgelli	NARRANDERA	34 20 00 S	146 08 00 E
Willandra Creek	BOOLIGAL	33 10 00 S	144 45 00 E
Willandra Creek/Lakes	POONCARIE	33 15 00 S	143 45 00 E
Wimmera River	HORSHAM	36 25 00 S	141 59 00 E
Winnambool	BALRANALD	34 57 00 S	142 44 00 E
Woakwine Range	PENOLA	37 18 00 S	139 57 00 E
Woodstock	BENDIGO	36 47 00 S	144 02 00 E
Woorinen	SWAN HILL	35 18 00 S	143 27 00 E
Wunghnu	BENDIGO	36 09 00 S	145 26 00 E
Wycheproof	ST.ARNAUD	36 05 00 S	143 14 00 E
Yalca	DENILIQUIN	36 00 00 S	145 18 00 E
Yamba	RENMARK	34 16 00 S	140 52 00 E
Yanac	HORSHAM	36 13 00 S	141 27 00 E
Yarriamback Creek	HORSHAM	36 10 00 S	142 24 00 E
Yellangip	HORSHAM	36 07 00 S	142 18 00 E
Yielima	JERILDERIE	35 54 00 S	145 14 00 E
Younghusband Peninsula	BARKER	35 44 00 S	139 11 00 E
Zanci	POONCARIE	33 42 00 S	143 02 00 E

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APPENDIX 2

Index of stratigraphic units

APPENDIX 2 – INDEX OF STRATIGRAPHIC UNITS (page 1 of 5)

Unit	*Map Symbol*	*Age*	*Reference*
'Ancestral streams' (informal nomenclature)	Mainly included in Qa	Late Pleistocene to Holocene	Pels, 1964b, 1966, 1970, 1971
Bakara Calcrete (modified from Bakara Soil)	Included in Qca	Pleistocene to Holocene	Firman, 1966e, 1973
Bakara Soil (includes Bakara calcrete)	Included in Qca	Pleistocene to Holocene	Firman, 1963
Barwo Member of Shepparton Formation	Included in TQs	Pliocene to Quaternary	Tickell, 1977a
Blanchetown Clay	Qpc	Early Pleistocene	Spence, 1958; Firman, 1965a, 1973
Blanchetown Formation (now Blanchetown Clay)	Qpc	Early Pleistocene	Spence, 1958
Bookpurnong beds equivalents (now in Calivil Formation)	Included in Tpc	Late Miocene to Pliocene	Ludbrook, 1962a
Bookpurnong Formation (synonym of Bookpurnong beds)	Tpb	Late Miocene to Early Pliocene	Carter, 1985
Bookpurnong beds	Tpb	Late Miocene to Early Pliocene	Ludbrook, 1957
Bridgewater Formation	Qpb	Late Pleistocene	Boutakoff & Sprigg, 1953; Boutakoff, 1963; Firman, 1966a
Brown Coal Sequence (now Moorlands Lignite Member)	Part of Teo	Late Eocene	McGarry, 1953
Buccleuch Bed A	Included in Teb	Late Eocene	Ludbrook, 1957
Buccleuch Bed B	Included in Teb	Late Eocene	Ludbrook, 1957
Buccleuch Bed C	Included in Teb	Late Eocene	Ludbrook, 1957
Buccleuch Group	Teb	Late Eocene to Early Oligocene	Ludbrook, 1961a
Buccleuch beds	Teb	Eocene? to Early Oligocene	Ludbrook, 1957
Bungunnia Limestone	Included in Qpc	Pleistocene	Firman, 1965a,b, 1973
Bungunnia Limestone equivalents	Equivalent to Qpc	Pleistocene	Rogers, 1980a
Bunyip Sand	Qdp	Late Quaternary	Firman, 1966c
Bymue Layer	Included in Qdw	Late Pleistocene	Churchward, 1960, 1961, 1963a,b
Bymue Member of Woorinen Formation	Included in Qdw	Late Pleistocene	Lawrence, 1966
Cadell equivalent &			
Cadell Marl Lens of Morgan Limestone	Included in Tml	Early Miocene	Ludbrook, 1957, 1961a
Calivil Formation	Tpc	Late Miocene to Pliocene	Macumber, 1973
Calivil Sand (now Calivil Formation)	Tpc	Late Miocene to Pliocene	Lawrence, 1975
Callabona Soil/Clay (top of Pooraka Formation)	Included in Qfr	Late Pleistocene to Holocene	Firman, 1970a, 1973
Cape Jervis beds (now Urana Formation in Murray Basin)	Pl	Late Carboniferous to Early Permian	O'Brien, 1981
Chowilla Sand (western equivalent to Shepparton Formation)	Included in TQs or Qpc	Pleistocene	Firman, 1973; Gill, 1973a
Cohuna Silt	Included in Ql	Late Quaternary	Thorne & Macumber, 1972; Macumber, 1977, 1983
Colongulac dune parna	Included in Qdl	Late Pleistocene to Holocene	Butler, 1958
Compton Conglomerate of Glenelg Group (Otway Basin) & Murray Group (Murray Basin)	Toc	?Mid to Late Oligocene	Ludbrook, 1957
Coomandook Formation	Qpl	Early Pleistocene	Firman, 1967b, 1973
Coombool Member of Monash Formation	Included in Kl	Early Cretaceous	Thornton, 1972, 1974
Coonambidgal Formation of Wunghnu Group	Included in Qa	Late Pleistocene to Holocene	Butler, 1958; Lawrence, 1966, 1975
Coorabin Coal Measures	Pu	Late Permian	Standing Committee on Coalfield Geology, 1976
Coreen Creek Coal Member of Coorabin Coal Measures	Included in Pu	Late Permian	Standing Committee on Coalfield Geology, 1976
Diapur Sandstone (now in Loxton–Parilla Sands)	Tps	Late Miocene to Pliocene	Lawrence, 1966
Dorodong Sandstone (Otway Basin)	contiguous with Tps	Pliocene	Kenley, 1962, 1971
Duddo Limestone of Murray Group	Included in Tml	Oligocene to Middle Miocene	Lawrence, 1966, 1975
Dunedin Park Sand – Member of Lake Victoria Sand	Included in Qdl	Recent	Gill, 1973a
Echuca Formation (now Torrumbarry Clay)	Included in Tpc	Late Miocene to Early Pliocene	Tickell, 1977a
Ettrick Formation of Murray Group	Toe	Oligocene to Early Miocene	Ludbrook, 1961a
Ettrick Marl (now Ettrick Formation)	Toe	Oligocene to Early Miocene	Lawrence, 1975
Ettrick Marls (now Ettrick Formation)	Toe	Oligocene to Early Miocene	Ludbrook, 1957
Finniss Clay of Murray Group	Included in Tml	Late Oligocene to Early Miocene (Murray Basin)	O'Driscoll, 1960; Ludbrook, 1961a

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Unit	*Map Symbol*	*Age*	*Reference*
Gambier Limestone of Glenelg Group (Otway Basin) & Murray Group (Murray Basin)	Included in Tml	Late Oligocene to Early Miocene (Murray Basin)	Sprigg, 1952a; Ludbrook, 1957, 1961a
Gambier Limestone Lower Member (Otway Basin only)	Included in Tml	Eocene – Oligocene	Ludbrook, 1961a
Gambier Limestone Upper Member (Otway Basin only) (Naracoorte Limestone Member in Murray Basin)	Included in Tml	Miocene	Ludbrook, 1961a
Gastropod Bed of Middle Murravian Series (now Cadell Marl)	Included in Tml	Early Miocene	Tate, 1885
Geera Clay of Murray Group	Tmg	Late Oligocene to Middle Miocene	Lawrence, 1966, 1975
Glanville Formation	Included in Qcl	Late Pleistocene	Firman, 1973; Rogers 1980b
Glenelg Group (Otway Basin)		Tertiary	Sprigg & Boutakoff, 1953; Ludbrook, 1957
Golgol unit (Lake Mungo lunette)	Included in Qdl	Pleistocene	Bowler, 1971, 1973, 1976b, 1978b
Gordon Limestone (synonym of Pata Limestone)	Included in Tml	Middle Miocene	Ludbrook in O'Driscoll, 1956
Goulburn Complex (informal terminology)	Included in Qa	Mainly Holocene	Bowler, 1978a
Green Gully Complex	Included in TQs/Qa	Late Pleistocene	Bowler, 1978a
Irymple Member of Blanchetown Clay	Included in Qpc	Early Pleistocene	Lawrence, 1972, 1975, 1976a, 1988a; Lawrence & Goldberry, 1973
Janjukian Series	Includes Tml, Toe, Teo, Tmw, Tmg	Oligo-Miocene	Hall & Pritchard, 1902; Chapman, 1916
Jerilderie Formation	TRm	Mid-Triassic	Standing Committee on Coalfield Geology, 1976
Kalimnan Clay (mainly Bookpurnong beds in Murray)	Tpb	Late Miocene to Early Pliocene	Hall & Pritchard, 1902; Chapman, 1916
Kalimnan Series (mainly Bookpurnong beds in Murray)	Tpb	Late Miocene to Early Pliocene	Chapman, 1916
Kanmantoo Group (Kanmantoo Fold Belt)		?Late Proterozoic to Cambrian (mainly Cambrian)	
Kanyapella silts	Included in Ql	Late Pleistocene	Bowler & Harford, 1966b
Katandra Depositional System	Included in TQs	Late Pleistocene	Butler, 1958
Katandra Member of Shepparton Formation	Included in TQs	Late Pleistocene	Lawrence, 1966, 1975, 1976a, 1988a
Keppoch Member of Padthaway Formation	Included in Qcl	Late Pleistocene	Harris, 1973; Rogers, 1980a
Kerang Sand Member of Loxton – Parilla Sands	Included in Tps	?Late Miocene to Early Pliocene	Macumber, 1978a,b, 1983
Kialla Member of Shepparton Formation	Included in TQs	Late Tertiary to Quaternary	Lawrence, 1966, 1975, 1976a, 1988a
Knight Formation (Otway Basin)	Part equivalent to Ter	Middle Eocene	Harris, 1966
Knight Group (now Renmark Group in Murray)	Ter (Teo & Tew)	?Paleocene to Middle Miocene	Sprigg & Boutakoff, 1953; Ludbrook, 1957, 1961a
Knight Group Lower (now Warina Sand in Murray)	Tew	?Paleocene to Eocene	Derrington & Anderson, 1970
Knight Group Upper (now Olney Formation in Murray)	Teo	Eocene to Middle Miocene	Ludbrook, 1971
Knight Sands and Clays (now Renmark Group in Murray)	Ter (Teo & Tew)	?Paleocene to Middle Miocene	Sprigg, 1952a
Knight beds (now Renmark Group in Murray)	Ter (Teo, Tew)	?Paleocene to Middle Miocene	Firman, 1973
Kongorong Sand of Gambier Embayment	Included in Ter	Eocene	Ludbrook, 1971
Kotupna Complex (informal terminology)	Included in Qa	Late Pleistocene	Bowler, 1978a
Kow Sand	Included in Qdl	Late Pleistocene but mainly Holocene	Thorne & Macumber, 1972; Macumber, 1977
Kyalite Layer (now Kyalite Member of Woorinen Formation)	Included in Qdw	Late Pleistocene	Churchward, 1960, 1963a; Lawrence, 1966
Kyalite Member of Woorinen Formation	Included in Qdw	Late Pleistocene	Lawrence, 1966
Laceby Gravel Member of Shepparton Formation	Included in TQs	Pliocene to Quaternary	Tickell, 1977a
Lacepede Formation of Gambier Embayment	Equivalent to Ter, formerly correlated with Teb	Eocene	Ludbrook, 1971
Lake Victoria Sands	Included in Qdl	Late Pleistocene to Holocene	Gill, 1973a
Lanes Shaft Coal Member of Coorabin Coal Measures	Included in Pu	Late Permian	Standing Committee on Coalfield Geology, 1976

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Unit	*Map Symbol*	*Age*	*Reference*
Loughmore Formation of Coorabin Coal Measures	Included in Pu	Late Permian	Standing Committee on Coalfield Geology, 1976
Loveday Soil	Included in Qca	Late Pleistocene	Firman, 1966d, 1972
Lowan Sand (Vic, part equivalent to Molineaux Sand SA)	Included in Qdm	Late Pleistocene to Holocene	Lawrence, 1966, 1975
Loxton Sands	Included in Tps	Pliocene	Ludbrook, 1957, 1961a
Loxton Sands Lower	Included in Tps	Early Pliocene	Firman, 1965b, 1966d, 1973
Loxton Sands Upper	Included in Tps	Early Pliocene	Firman, 1965b, 1966d, 1973
Loxton–Parilla Sands (undifferentiated)	Tps	Late Miocene to Pliocene (mainly Pliocene)	this Bulletin
Mannum Formation of Murray Group	Included in Tml	Oligocene to Early Miocene	Ludbrook, 1957, 1961a
Mayrung Member of Shepparton Formation	Included in TQs	Late Pleistocene	Lawrence, 1966, 1975, 1976a, 1988a
Mayrung System / Mayrung beds	Included in TQs	Late Pleistocene	Butler, 1958
Merretti Member of Monash Formation	Included in Kl	Early Cretaceous	Thornton, 1972, 1974
Millewa Group	Included in Kl	Early Cretaceous	Lawrence, 1972, 1975; Lawrence & Goldberry, 1973
Miralie Member of Woorinen Formation	Included in Qdw	Late Pleistocene	Lawrence, 1966
Molineaux Sand (SA part equivalent to Loxton Sand in Vic)	Included in Qdm	Late Pleistocene to Holocene	Firman, 1965b, 1966b, 1973
Monash Formation	Included in Kl	Early Cretaceous	Thornton, 1972, 1974
Monoman Formation (equivalent to upper TQs or Qa)	Included in Qa	Late Pleistocene to Holocene	Firman, 1966c, 1973
Moorlands Coal Measures (now Moorlands Lignite Member)	Included in Teo	Eocene to Middle Miocene	Ludbrook, 1961a
Moorlands Lignite Member of Olney Formation	Included in Teo	Eocene to Middle Miocene	Harris, 1966
Moorna Formation	Included in TQs	Pleistocene	Gill, 1973a
Morgan Limestone of Murray Group	Included in Tml	Early to Middle Miocene	Tate, 1885; Ludbrook, 1957, 1961a
Morgan Limestone Lower	Included in Tml	Early Miocene	Ludbrook, 1961a
Morgan Limestone Middle Marly Unit (equivalent to Winnambool Formation)	Included in Tml, but equivalent to Tmw	Miocene	Lindsay & Bonnett, 1973
Morgan–Mannum equivalents (now Winnambool Formation or Geera Clay)	Included in Tmw or Tmg	Oligocene to Middle Miocene	Ludbrook, 1961a; Rodgers, 1978
Morgan–Mannum Limestone (informal nomenclature)	Included in Tml	Oligocene to Middle Miocene	
Morkalla Formation of Millewa Group	Included in Kl	Early Cretaceous	Lawrence, 1972, 1975; Lawrence & Goldberry, 1973
Mount Gambier Limestone (now Gambier Limestone) of Gambier Embayment	Included in Tml	Eocene to Middle Miocene	Tenison-Woods, 1865
Mount Gambier stone (now Gambier Limestone) of Gambier Embayment	Included in Tml	Eocene to Middle Miocene	Tenison-Woods, 1862
Mungo unit (Lake Mungo lunette)	Included in Qdl	Late Pleistocene	Bowler, 1971, 1973, 1976b, 1978b
Murravian Series	Mainly included in Tml	Oligocene to Middle Miocene	Tate, 1878
Murray Group	Toc, Toe, Tml, Tmg, Tmw	Oligocene to Middle Miocene	Ludbrook, 1957; Lawrence & Abele, 1976, 1988
Murray Group Limestone (informal nomenclature)	Tml	Oligocene to Middle Miocene	
Murray Group calcarenites (informal nomenclature)	Tml	Oligocene to Middle Miocene	
Naracoorte Limestone (now Naracoorte Limestone Member)	Included in Tml	Early Miocene	Ludbrook, 1957
Naracoorte Limestone Member of Gambier Limestone	Included in Tml	Early Miocene	Ludbrook, 1957
Narrow Plains Formation of Coorabin Coal Measures	Included in Pu	Late Permian	Standing Committee on Coalfield Geology, 1976
Netherby Marl (now Ettrick Formation)	Toe	Oligocene to Early Miocene	Lawrence, 1966
Newer Volcanics	TQv	Late Tertiary to Quaternary	Hills, 1938; Ellis & Ferguson, 1976; Price & others, 1988; Johnson, 1989
Norwest Bend Formation	Tpn	Late Pliocene	Tate, 1885; Ludbrook, 1957, 1961a
Norwest Bend beds (now Norwest Bend Formation)	Tpn	Late Pliocene	Tate, 1885; Spence, 1958
Nowranie Creek Formation of Coorabin Coal Measures	Included in Pu	Late Permian	Standing Committee on Coalfield Geology, 1976
Nulla Nulla Sand Member of Lake Victoria Sand	Included in Qdl	Late Pleistocene to Holocene	Gill, 1973a
Olney Formation of Renmark Group	Teo	Eocene to Middle Miocene	Lawrence, 1975
Otway Group of Otway Basin	Included in Kl	Cretaceous	Wopfner & Douglas, 1971

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Unit	*Map Symbol*	*Age*	*Reference*
Padthaway Formation	Qcl	Late Pleistocene	Harris, 1973; Rogers, 1980a
Parilla Sand (SA)	Included in Tps	Late Pliocene	Firman, 1965b, 1966a,d
Parilla Sand (Vic – now Loxton–Parilla Sands)	Tps	Late Miocene to Pliocene (mainly Pliocene)	Lawrence, 1975
Pata Limestone equivalents (now Winnambool Formation or Geera Clay)	Tmw or Tmg	Miocene	Ludbrook, 1961a; Rogers, 1978
Pata Limestone of Murray Group	Included in Tml	Middle Miocene	Ludbrook, 1957, 1961a
Piangil Layer (now Piangil Member of Woorinen Formation	Included in Qdw	Late Pleistocene	Churchward, 1963a
Piangil Member of Woorinen Formation	Included in Qdw	Holocene	Lawrence, 1966
Pooraka Formation	Included in Qfr	Early Pleistocene to Holocene	Firman, 1966f
'Prior streams' (informal nomenclature)	Included in TQs	Late Pleistocene	Butler, 1950
Pyap Member of Monash Formation	Included in Kl	Early Cretaceous	Thornton, 1972, 1974
Quiamong Depositional System	Included in TQs	Late Pleistocene	Butler, 1958
Quiamong Member of Shepparton Formation	Included in TQs	Late Pleistocene	Butler, 1958; Lawrence, 1966, 1975, 1976a, 1988a
Ramco Stone (informal unit of Norwest Bend Formation)	Included in Tpn	Late Pliocene	Ludbrook, 1961a
Renmark Group	Ter (Teo & Tew)	?Paleocene to Middle Miocene	Lawrence, 1975
Renmark Group Lower (now Warina Sand)	Tew	?Paleocene–Eocene	Thornton, 1974
Renmark beds (now Renmark Group)	Ter (Teo & Tew)	?Paleocene to Middle Miocene	Harris, 1966
Renmark beds Lower (now Warina Sand)	Tew	?Paleocene to Eocene	Thornton, 1974
Renmark beds Upper (now Olney Formation)	Teo	Eocene to Middle Miocene	Thornton, 1974
Ripon Calcrete	Included in Qca	Pleistocene to Holocene	Firman, 1967b, 1973
Rufus Formation	Included in TQs	Pleistocene	Gill, 1973a
Semaphore Sand	Qhe	Holocene	Thomson, 1969a; Firman, 1973
Shepparton Formation of Wunghnu Group	TQs	Late Tertiary to Quaternary	Lawrence, 1966, 1975
Speewa Layer (now Speewa Member of Woorinen Formation)	Included in Qdw	Late Pleistocene	Churchward, 1960; Lawrence, 1966
Speewa Member of Woorinen Formation	Included in Qdw	Late Pleistocene	Lawrence, 1966
St. Kilda Formation	Qho	Holocene	Sprigg, 1952a; Firman, 1973
Talgarry Sand Member of Lake Victoria Sands	Included in Qdl	Holocene	Gill, 1973a
Tallygaroopna Complex (informal terminology)	Included in TQs/Qa	Late Pleistocene	Bowler, 1978a
Taparoo Sandstone of Millewa Group	Included in Kl	Early Cretaceous	Lawrence, 1972, 1975; Lawrence & Goldberry, 1973
Tartangan beds (equivalent to Coonambidgal Formation & Bunyip Sand)	Included in Qa	Holocene	Hale & Tindale, 1930; Tindale, 1957; Firman, 1971b, 1973
Tartwaup Formation of Knight Group, Gambier Embayment	Included in Ter	Middle Eocene	Ludbrook, 1971
Tawonga Gravel	Included in Qfr	Quaternary	Beavis, 1962; Lawrence, 1975, 1976a, 1988a
Tooleybuc Layer (now Miralie Member of Woorinen Formation)	Included in Qdw	Late Pleistocene	Churchward, 1960, 1961, 1963a,b
Torrumbarry Clay	Mostly included in Tpc	Miocene to Pliocene	Lawrence, 1975
Torrumbarry Clay Member of Shepparton Formation (now Torrumbarry Clay)	Included in Tpc	Pliocene	Tickell, 1977a
Tragowel Member of Loxton–Parilla Sands	Included in Tpc	Pliocene	Macumber, 1978a,b, 1983
Urana Formation	Pl	Late Carboniferous to Early Permian	O'Brien, 1986
Waaia Member of Shepparton Formation	Included in TQs	Pliocene to Quaternary	Tickell, 1977a
Waikerie Freestone (informal unit of Norwest Bend Formation)	Included in Tpn	Late Pliocene	Ludbrook, 1961a
Wandella Sandstone Member of Loxton–Parilla Sands	Included in Tps	Pliocene	Macumber, 1978a,b, 1983
Warina Sand of Renmark Group	Tew	?Paleocene to Eocene	Lawrence, 1975
Weerikooian Series (Loxton–Parilla Sands in Murray Basin)	Tps	Pliocene	Chapman, 1916
Widgelli Member (now Widgelli Pedoderm)	Included in TQs	Late Pleistocene	Butler, 1958; Lawrence, 1966

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Unit	*Map Symbol*	*Age*	*Reference*
Widgelli Parna – part of Shepparton Formation	Included in TQs	Late Pleistocene	Butler, 1956, 1958; Butler & Hutton (1956)
Widgelli Pedoderm – part of Shepparton Formation	Included in TQs	Late Pleistocene	Butler, 1958; Lawrence, 1975, 1976a, 1988a
Winnambool Formation of Murray Group	Tmw	Late Oligocene to Middle Miocene	Lawrence, 1966, 1975
Woorinen Formation	Qdw	Late Pleistocene to Holocene	Lawrence, 1966
Wunghnu Group	Tpc, TQs, Qa	Late Miocene to Holocene	Lawrence, 1966, 1975
Yalca Member of Shepparton Formation	Included in TQs	Pliocene to Quaternary	Tickell, 1977a
Yamba Formation	Qly	Late Pleistocene to Holocene	Firman, 1966c, 1973
Yanac Member of Ettrick Formation (formerly Netherby Marl)	Included in Toe	?Mid to Late Oligocene	Lawrence, 1966
Yando Clay Member of Shepparton Formation	Included in TQs	Pliocene	Macumber, 1983
Yielma Member of Shepparton Formation	Included in TQs	Pliocene to Quaternary	Tickell, 1977a
Zanci unit (Lake Mungo lunette)	Included in Qdl	Late Pleistocene,	Bowler, 1971, 1973, 1976b, 1978b

APPENDIX 3

Common abbreviations

APPENDIX 3 – COMMON ABBREVIATIONS

Abbreviation	
A.A.O	Associated Australian Oilfields No Liability
A.O.C.	Australian Oil Corporation
A.O.D.	Alliance Oil Development Australia No Liability
A.O.G.	Australian Oil and Gas Corporation Limited
A.P.E.	Amalgamated Petroleum Exploration
Anglo American	Anglo American Corporation (Australia) Limited
BHP	Broken Hill Proprietary Company Limited
BHP Petroleum	BHP Petroleum Proprietary Limited
BMR	Bureau of Mineral Resources, Geology and Geophysics, Australia
Beach	Beach Petroleum No Liability
Beaver	Beaver Exploration No Liability
Company bore	Loxton Farm Company
CRA	Conzinc Riotinto Australia Limited
Comserv	Comserv (No. 779) Proprietary Limited
CSR	Colonial Sugar Refiners Limited
D.I.T.R.	Department of Industry Technology and Resources, Victoria
ESSO	ESSO Exploration and Production Australia or ESSO Australia Limited
G.L. / g.l.	ground level, relative to sea-level
K.B. / k.b.	Kelly bushing (on drilling platform)
M.B.O.S.	Murray Basin Oil Syndicate
Mid-Eastern	Mid-Eastern Oil No Liability
Mideastern	Mideastern Oil No Liability
N.A.P.	North Australian Petroleum Company
NSW D.M.	New South Wales Department of Mines
NSW DWR	New South Wales Department of Water Resources
NSW Oil & Gas	New South Wales Oil and Gas Company Limited
North Star	North Star Oil Corporation
O.D.N.L.	Oil Development No Liability
Planet	Planet Management and Research Proprietary Limited or Planet Exploration Company Proprietary Limited or Planet Oil Company
SADME	South Australian Department of Mines and Energy
S.A.O.G.C.	South Australian Oil & Gas Corporation
Texam	Texam Oil Corporation
T.D. / t.d.	total depth
Vic. D.M.	Victorian Department of Mines
W.R.C.	Water Resources Commission of New South Wales
Woodside	Woodside (Lakes Entrance) Oil Company No Liability

APPENDIX 4

Age determinations

APPENDIX 4 – AGE DETERMINATIONS (page 1 of 6)

Site	*Location*	*Type*	*Age*	*Unit(s)*	*Reference*
Boreholes	NW Victoria	Foraminifera	Tertiary	Ter, Tml, Tmw, Tpb	Abele, 1970
Boreholes	Horsham area, Vic.	Foraminifera	Miocene – Pliocene	Tml	Abele, 1977
Surface	Lake Tandou, N.S.W.	Radiocarbon	Late Pleistocene	Qdl	Allen, 1972
Boreholes	Lake Tyrrell, Vic.	Palaeomagnetism	Late Pleistocene	Qpc	An Zhi – Sheng & others, 1986
Surface	Lake Cawndilla, N.S.W.	Marsupials	Late Pleistocene – Holocene	Qdl	Aplin & others, 1981
Surface	Murray River	Marsupials	Quaternary	Rock shelters	Archer, 1971
Boreholes	S.E. Riverine Plain	Palynology	Eocene – Pliocene	Teo, Tpc	Archer, 1983
Olney 1	34 05 55 S 141 01 12 E	Palynology	Eocene – Pliocene	Ter, Toe, Tmw ,Tml, Tpb	Archer, 1984
Surface	Murray Basin, Vic.	K – Ar	Late Miocene – Pliocene	TQv	Aziz – Ur – Rahman & McDougall, 1972
Surface	Western N.S.W.	Magnetic		Aboriginal fireplaces	Barbetti, 1973
Surface	Lake Mungo, N.S.W.	Aboriginal fireplaces	Late Pleistocene – Holocene	Qdl	Barbetti & Allen, 1972
Surface	Western N.S.W.	Radiocarbon	Late Pleistocene – Holocene	Qdl	Barbetti & Polach, 1973
Surface	Mount Gambier & Mount Schank, S.A.	Palaeomagnetism	Late Quaternary	TQv	Barbetti & Sheard, 1981
Core samples	Mount Gambier, S.A.	Magnetic & radiocarbon	Late Pleistocene – Holocene	TQv	Barton & McElhinny, 1980
Surface	Cosgrove, Vic.	K – Ar	Tertiary	Tv	Birch, 1976
Surface	Mount Gambier, S.A.	Radiocarbon	Holocene	TQv	Blackburn, 1966b
Surface	Mount Gambier, S.A.	Radiocarbon	Holocene	TQv	Blackburn & others, 1982
Surface	Victorian Highlands	K – Ar	Tertiary	Tv	Bowen, 1974
Surface	Goulburn River Valley, Vic.	Radiocarbon	Holocene	Qa – Coonambidgal	Bowler, 1967
Surface	Lake Nitchie, N.S.W.	Radiocarbon	Late Quaternary	Aboriginal remains, Qdl	Bowler, 1970b
Surface	Lake Mungo, N.S.W.	Radiocarbon	Late Pleistocene	Qdl	Bowler, 1980
Surface	Riverine Plain, near Echuca	Radiocarbon	Late Pleistocene – Holocene	TQs, Qa	Bowler & Harford, 1966b
Surface	Riverine Plain, Vic.	Radiocarbon	Late Pleistocene – Holocene	TQs, Qa	Bowler & Polach, 1971
Near surface	Lake Tyrrell, Vic	Radiocarbon	Late Pleistocene	Tyrrell beds (Qly)	Bowler & Teller, 1986
Boreholes	Murrayville – Ouyen, Vic.	Foraminifera & macrofossils	Oligocene – Pliocene	Tps, Tpb, Tml	Chapman, 1916
Surface & boreholes	Mallee region, Vic.	Ostracods & foraminifera	Pleistocene & Oligocene – Miocene	Qpc, Tml	Chapman, 1936
Surface	Coonalpyn, S.A.	Foraminifera	Tertiary	Tertiary sediment	Chapman, 1943
Boreholes		Macrofossils	Pliocene – Holocene	Tps	Chapman & Gabriel, 1914
Boreholes	Padthaway area, S.A.	Radiocarbon & foraminifera	Pliocene – Holocene	Tps, Qcl	Cook & others, 1977
Borehole	Canopus, S.A.	Palynology	Tertiary		Cookson, undated
Surface	Naracoorte, S.A.	Foraminifera	Tertiary		Cooper, 1981
Boreholes	Dimboola, Vic.	Foraminifera	Oligocene – Pliocene	Tps, Tpb, Tml	Crespin, 1946, 1947
Boreholes	Moorlands, S.A.	Foraminifera	Eocene – Miocene	Teb, Ter, Tml	Crespin, 1953
Surface & subsurface	S.E. Australia	Mollusca	Tertiary		Darragh, 1985
Surface	Victorian Highlands	K – Ar	Tertiary	Tv	Day, 1983
Surface	Angas River, S.A.	Radiocarbon	Holocene	Qa	Dury, 1964
Boreholes	Murrumbidgee River Valley, N.S.W.	Radiocarbon	Late Pleistocene – Holocene	Groundwater	Drury, 1982
Wentworth 1	33 48 45 S 141 58 15 E	Palynology	Early Cretaceous, Early Permian	Kl Pl	Evans, 1962
Jerilderie 1	35 15 00 S 145 58 00 E	Palynology	Early Permian, Late Permian	Pu, Pl, DCls	Evans, 1963
Blantyre 1	32 09 15 S 143 09 40 E	Palynology	Devonian, Early Carboniferous	DCls	Campe & Cundill, 1965

Site	*Location*	*Type*	*Age*	*Unit(s)*	*Reference*
Berri North 1	34 12 17 S 140 38 06 E	Palynology	Early Cretaceous, Early Permian	Kl, Pl	Evans, 1967a
			Famennian	DCls	Evans, 1968
Boreholes	Western Murray Basin	Palynology	Early Cretaceous	Kl	Evans & Hawkins, 1967
Petroleum wells	Western N.S.W.	Palynology	Tertiary	Ter, Tpc, Tmw, Tml Tmg, Tpb	Evans & Hodgson, 1963
Surface	Mount Gambier, S.A.	Radiocarbon	Holocene	TQv	Fergusson & Rafter, 1957
Borehole	Murray Basin, S.A.	Radiocarbon	Holocene	Qa – Cooambidgal & Monoman Formations	Firman, 1967b
Surface	Yorke Peninsular, S.A.	Palynology	Early Permian	Pl	Foster, 1974
Surface	Western Murray Basin	Thermoluminescence & radiocarbon	Late Pleistocene – Holocene	Qly, Qdm	Gardner & others, 1987
Surface	Mount Gambier, S.A.	Radiocarbon	Holocene	TQv	Gill, 1955b
Surface		Radiocarbon	Late Pliocene – Holocene	Australites	Gill, 1965
Surface	Mallee of N.W. Vic.	Radiocarbon	Late Quaternary	Quaternary sediment	Gill, 1966
Surface	Murray Basin, Vic.	Radiocarbon	Late Quaternary	Quaternary sediment	Gill, 1971
Surface	Tower Hill, Vic.	Radiocarbon	Holocene	TQv	Gill, 1972
Surface	Lake Victoria, N.S.W.	Radiocarbon	Late Pleistocene – Holocene	TQs, Ql, Qdl, Qa, Qdw	Gill, 1973a
Surface	Western Vic. & Mallee of N.W. Vic.	Radiocarbon	Late Quaternary	TQv	Gill, 1978
Surface	Mitiamo, Vic.	Radiocarbon	Holocene	Aboriginal remains	Gill, 1980
Surface	Narrandera, N.S.W.	Radiocarbon	Late Pleistocene – Holocene	Quaternary sediment	Gill & Bethune, 1976
Surface	Mount Napier, Vic.	Radiocarbon	Late Quaternary	TQv	Gill & Elmore, 1973
Surface	Western Vic.	Radiocarbon	Late Quaternary	TQv	Gill & Gibbons, 1969
Surface & subsurface	S.E. Australia	Foraminifera	Tertiary		Glaessner, 1951
Surface	Western Vic.	Fission track	Early Cretaceous	Kl	Gleadow & Duddy, 1987
Surface	Murray River	Vertebrate & macrofossils	Quaternary	Rock shelter	Hale & Tindale, 1930
North Renmark 1	34 07 00 S 140 41 00 E	Palynology			Harris, 1963
Lake Victoria 1	34 03 15 S 141 20 53 E	Palynology		Kl, Ter, Tpb	Harris, 1964
Monash 1	34 12 00 S 140 29 57 E	Palynology			Harris, 1965
Boreholes	Murray Basin, S.A.	Palynology	Early Tertiary	Tew, Teo, Ter	Harris, 1970
Boreholes	Gambier Embayment	Palynology	Tertiary	Tertiary sediment	Harris, 1971
Morkalla 1	34 22 25 S 141 09 55 E	Palynology	Palaeocene – Eocene	Tew, Teo, Ter	Harris, 1973
subsurface	Coastal Murray Basin & Gambier Embayment	Palynology	Middle to Late Eocene	Ter	Harris, 1985
Boreholes	Oaklands Basin	Palynology	Eocene	Ter	Harris & Morgan, 1976
Mount Emu 1	Blantyre Trough, N.S.W.	Palynology	Tertiary Middle – Lower Devonian	Ter, DCls, SDls	Haskell, 1970c
Gunamalary 2	Murrayville, Vic.	Palynology	Late Carboniferous – Early Permian	Pl	Helby, 1986
Surface	Menindee & Willandra Lakes, N.S.W.	Marsupials	Late Pleistocene – Holocene	Qdl	Hope, 1978
Surface	Lake Tandou, N.S.W.	Marsupials	Pleistocene	Qdl	Hope & others, 1983
Near surface	Gambier Embayment	Palaeomagnetism	Quaternary	Qpb	Idnurm & Cook, 1980
Surface	Nildottie, S.A.	Macrofauna – spider crabs	Oligocene – Miocene	Tml	Jenkins, 1985
BMR Ivanhoe 1	Ivanhoe, N.S.W.	Macro & microfossils	Early Devonian	SDls	Jones & others, 1981

Site	*Location*	*Type*	*Age*	*Unit(s)*	*Reference*
Boreholes	Central Murray Basin	Palynology	Late Cainozoic	Quaternary & Tertiary	Knight & Martin (1989)
Coal bores	Anna Coalfield, S.A.	Palynology & foraminifera	Eocene – Pliocene	Tpn, Tml, Toe, Ter	Kress & others,1978
Surface	Murray River cliffs, S.A.	Macrofossils – echinoids	Oligocene – Miocene	Tml	Kruse & Philip, 1985
Surface	Riverine Plain	Radiocarbon	Late Quaternary	TQs Qa	Langford – Smith, 1963
Surface	Riverine Plain, N.S.W.	Radiocarbon	Late Pleistocene – Holocene	Qa	Langford – Smith, 1966
Boreholes	Waikerie, S.A.	Foraminifera	Eocene – Miocene	Ter, ?Teb, Tml	Lindsay, 1965a,b
Boreholes & surface	Waikerie & Pyap, S.A.	Foraminifera	Eocene – Miocene	Ter, ?Teb, Tml	Lindsay, 1966
Boreholes	Millicent, S.A.	Foraminifera	Oligocene – Miocene	Tml	Lindsay, 1967a
Shallow boreholes	Monteith, S.A.	Foraminifera	Oligocene – Miocene	Tml	Lindsay, 1967b
Surface & boreholes	Lake Victoria, N.S.W. & Chowilla, S.A.	Foraminifera	Miocene – Pliocene	Tml, Tpb, Tps	Lindsay, 1972
Surface	Peake area, S.A.	Foraminifera	Pliocene	Tps	Lindsay, 1977
Oakvale 1	32 59 03 S 140 54 09 E	Foraminifera	Oligocene – Miocene – Pliocene	Toe, Tmg, Tps	Lindsay, 1982a, 1983a
Borehole	S.W. Murray Basin	Foraminifera	Oligocene – Miocene	Tml	Lindsay, 1982b
Surface	Mannum, S.A.	Foraminifera	Oligocene – Miocene	Tml	Lindsay, 1982c
Boreholes	Murray Basin, S.A.	Foraminifera	Tertiary	Ter, Teb, Toe, Tml	Lindsay, 1985a
Borehole	Neckarboo Ridge, N.S.W.	Foraminifera	Oligocene – Miocene	Tmg, Tmw	Lindsay, 1987
Waikerie bores	34 11 34 S 139 58 48 E	Foraminifera	Eocene – Pliocene	Ter, ?Teb, Toe, & Tml, Tpn	Lindsay & Bonnett, 1973
Surface	Murray River Gorge, S.A.	Foraminifera	Oligocene – Miocene	Tml	Lindsay & Giles, 1973
Surface	Hartly & Monarto, S.A.	Foraminifera	Oligocene – Miocene	Toc, Toe, Tml	Lindsay & Williams, 1977
Loxton 1	34 34 00 S 140 39 00 E	Foraminifera	Early Cretaceous, Tertiary	Kl, Ter, Tml, Tpb, Tps	Ludbrook, 1956
Shallow bores, & surface	Swan Reach, S.A.	Foraminifera	Oligocene – Miocene	Tml	Ludbrook, 1958b
Surface	Murray Basin, S.A.	Macrofauna	Pliocene	Tps	Ludbrook, 1959
Surface, & subsurface	Chowilla, S.A.	Foraminifera	Miocene – Pliocene	Tml, Tpb, Tps	Ludbrook, 1960
Surface & subsurface	Western Murray Basin, S.A.	Foraminifera & macrofauna	Tertiary	Ter, Teb, Toe, Tml, & Tpb, Tps, Tpn	Ludbrook, 1961a
Surface	Western Murray Basin	Macrofossils	Miocene – Pliocene	Tml, Tpn	Ludbrook, 1961b
Balranald 1	34 39 20 S 143 29 32 E	Foraminifera	Eocene – Pliocene	Ter, Tmg, Tpc, Tps	Ludbrook, 1962a
Wentworth 1	33 48 45 S 141 58 15 E	Foraminifera	Early Permian, Early Cretaceous, & Tertiary	Pl, Kl, Ter, Toe, Tml, & Tmw, Tpb, Tps	Ludbrook, 1962b
Surface & subsurface	Western Murray Basin, S.A.	Foraminifera & macrofauna	Tertiary	Tertiary sediment	Ludbrook, 1963a
Penola 1	S.W. Murray Basin	Foraminifera	Tertiary	Ter, Tml, Tps	Ludbrook, 1963b
North Renmark 1	34 07 00 S 140 41 00 E	Foraminifera	Early Permian, Early Cretaceous, & Tertiary	Pl, Kl, Ter, Tml, Tpb, & Tps	Ludbrook, 1963c
Lake Victoria 1	34 03 15 S 141 20 53 E	Foraminifera	Early Cretaceous, Tertiary	Kl, Ter, Toe, Tml, Tpb	Ludbrook, 1964
Monash 1	34 12 00 S 140 29 51 E	Foraminifera	Early Permian, Early Cretaceous, & Tertiary	Pl, Kl, Ter, Toe, Tml, & Tpb	Ludbrook, 1965
Surface & subsurface	Murray Basin, S.A.	Foraminifera	Early Permian	Pl	Ludbrook, 1967b
Surface & subsurface	Gambier Embayment	Foraminifera & macrofauna	Tertiary	Tml	Ludbrook, 1967c, 1971

Site	*Location*	*Type*	*Age*	*Unit(s)*	*Reference*
Surface & subsurface	Southern Australia	Mollusca	Cainozoic	Tertiary sediment	Ludbrook, 1973
Surface & subsurface	South Australia	Foraminifera	Late Eocene	Mid-Tertiary sediment	Ludbrook & Lindsay, 1966
Near surface	Lake Tyrrell, Vic.	Radiocarbon	Late Quaternary	Qly	Luly & others, 1986
Boreholes	Manilla, N.S.W.	Palynology	Tertiary	Teo, Tmg	Macphail, 1987
Borehole	Piangil West 1, Vic.	Palynology	Tertiary	Teo, Tmg	Macphail, 1988a
Borehole	Woodlands, N.S.W.	Palynology	Tertiary	Teo, Tmg	Macphail, 1988b
Boreholes	Western Murray Basin	Palynology	Early Cretaceous, Tertiary	Kl, Teo, Tmg	Macpail & Truswell, 1988, 1989
Surface	Kow Swamp, Vic.	Radiocarbon	Late Pleistocene – Holocene	Ql, Qdl	Macumber, 1977
Quarry exposures	Gredgwin Ridge, Vic.	Macrofossils	Late Miocene – Pliocene	Tps	Macumber, 1978a
Surface	Lake Tyrrell, Vic.	Radiocarbon	Late Pleistocene – Holocene	Qly	Macumber, 1983
Surface	Lake Victoria, N.S.W.	Radiocarbon & vertebrate	Late Pliocene – Quaternary	TQs, Qpc Qdl, Qa	Marshall, 1973
Boreholes	Riverine Plain	Palynology	Tertiary	Ter, Tpc, TQs	Martin, 1973
Boreholes	Hay, Balranald, Wakool, N.S.W.	Palynology	Tertiary	Ter, Tpc, TQs	Martin, 1977
Boreholes	Riverine Plain, Southern N.S.W.	Palynology	Tertiary	Kl	Martin, 1984a
Boreholes	Murrumbidgee area, N.S.W.	Palynology	Permian, Cretaceous, Tertiary	Pl, Kl, Ter, Tpc	Martin, 1984b
Boreholes	Lachlan area, N.S.W.	Palynology	Cretaceous, Tertiary	Kl, Ter, Tpc	Martin 1984c
Boreholes	N. & E. Murray Basin	Palynology	Tertiary	Tertiary sediment	Martin, 1986a
Boreholes	N & E. Murray Basin	Palynology	Tertiary	Tertiary sediment	Martin, 1986b
Boreholes	Lachlan River area	Palynology	Tertiary	Tertiary sediment	Martin, 1987
Boreholes	Lake Menindee region, N.S.W.	Palynology	Tertiary	Tertiary sediment	Martin, 1988
Boreholes	Riverine Plain	Palynology	Cainozoic	Cainozoic sediment	Martin, 1989
Surface	Western Vic.	K–Ar	Late Cainozoic	TQv	McDougal & others, 1966
Surface	Western Vic.	K–Ar	Quaternary	TQv	McDougal & Gill, 1975
Borehole	Gambier Embayment, S.A.	Foraminifera	Tertiary	Tertiary sediment	McGowran, 1973
Surface & subsurface	South Australia	Foraminifera	Late Eocene	Late Eocene sediment	McGowran & Beecroft, 1985
Surface	Darling Region, N.S.W.	Marsupials	Late Pleistocene – Holocene	Qad, Qdl	McIntyre, 1981
Surface	Willandra Lakes, N.S.W.	Marsupials	Late Pleistocene – Holocene	Qdl	McIntyre & Hope, 1978
Surface	Moorna, N.S.W.	Ostracods	Pleistocene	Qpc	McKenzie & Gill, 1968
Surface	Victorian Highlands	Radiometric	Cainozioc	Tv, TQv	McKenzie & others, 1984
Boreholes	S.E. Riverine Plain	Palynology	Permian	Pl	McLeod, 1977
Boreholes	S.E. Riverine Plain	Palynology	Permian	Pl	McLeod, 1978
Boreholes	S.E. Riverine Plain	Palynology	Permian	Pl	McLeod, 1979
Boreholes	Jerilderie, Hay, Ivanhoe, N.S.W.	Palynology	Permian to Tertiary	Pl, Pu, TRm, Kl, Teo	McMinn, 1981
Avery 1	33 06 14 S 141 27 14 E	Palynology	Late Carboniferous, Early Permian Early Cretaceous, Tertiary	Pl, Kl, Ter	McMinn, 1986a
Kopi Plain 1	33 13 49 S 141 16 07 E	Palynology	Late Carboniferous, Early Permian, & Early Cretaceous	Pl, Kl	McMinn, 1986b
Surface	Lake Tandou, N.S.W.	Marsupials	Pleistocene	Qdl	Merrilees, 1973
Boreholes	Oaklands Basin, N.S.W.	Palynology	Permian, Triassic, Eocene	Pu, Pl	Morgan, 1975a
Jerilderie 1 & Urana 2	Oaklands Basin, N.S.W.	Palynology	Permian, Triassic, Tertiary	Ter, Pu, Pl, TRm	Morgan, 1975b

Site	*Location*	*Type*	*Age*	*Unit(s)*	*Reference*
Boreholes	Oaklands Basin, N.S.W.	Palynology	Permian	Pu, Pl	Morgan, 1976a
Boreholes	Oaklands Basin, N.S.W.	Palynology	Permian	Pu, Pl	Morgan, 1976b
Boreholes	Oaklands Basin, N.S.W.	Palynology	Permian, Triassic	Pu, Pl, TRm	Morgan, 1977a
Boreholes	Oaklands Basin, N.S.W.	Palynology	Carboniferous, Permian	Pl	Morgan, 1977b
Surface	Murray River, S.A.	Marsupials	Quaternary	Rock shelters	Mulvaney & others, 1964
Surface	Near Loxton, S.A.	Radiocarbon	Late Pleistocene	Qdm	Ohmori & Wasson, 1985
Borehole	Loddon Valley, Vic.	Palynology	Early Oligocene–Early Miocene	Teo	Partridge & Wilkinson, 1982
Petroleum wells	Paringa Embayment, S.A.	Palynology	Permian, Cretaceous, Tertiary	Pl, Kl, Tew, Teo, Toe	Paten & Price, 1970
Surface	Griffith, N.S.W.	Radiocarbon	Late Pliocene–Holocene	Qa 'ancestral streams'	Pels, 1964a
Surface & shallow bores	Riverine Plain	Radiocarbon	Late Pleistocene–Holocene	TQs, Qa	Pels, 1964b
Surface	Riverine Plain	Radiocarbon	Late Pleistocene–Holocene	TQs, Qa	Pels, 1966
Surface	Riverine Plain	Radiocarbon	Late Quaternary	TQs, Qa	Pels, 1969a
Surface	Riverine Plain	Radiocarbon	Late Quaternary	TQs, Qa	Pels, 1969b
Surface	Sunlands & Ramco, S.A.	Macrofossils	Pliocene	Tps	Pledge, 1985
Surface	Murray Basin	Radiocarbon	Late Quaternary	Quaternary sediments	Polach & others, 1978
Nulla Nulla 1	33 37 36 S 141 01 19 E	Palynology	Permo-Carbiniferous, Early Cretaceous & Tertiary	Pl, Kl, & Tertiary sediment	Powis, 1984a
Pamamaroo 1	32 10 22 S 142 29 42 E	Palynology	Devonian, Permo-Carboniferous, & Tertiary	DCls, Pl, & Tertiary sediment	Powis, 1984b
Ennisvale 1	33 18 15 S 141 11 23 E	Palynology	Permo-Carboniferous, Early Cretaceous & Tertiary	Pl, Kl, & Tertiary sediment	Powis, 1984c
Popiltah 1	33 22 39 S 141 41 31 E	Palynology	Permo-Carboniferous Early Cretaceous & Tertiary	Pl, Kl, & Tertiary sediment	Powis, 1984d
Surface	Mallee, Vic.	Thermoluminescence	Late Pleistocene	Qdw	Readhead, 1988
Nulla Nulla 1	33 37 36 S 141 01 19 E	Foraminifera	Early Cretaceous & Tertiary	Kl, & Tertiary	Rexilius, 1984a
Ennisvale 1	33 18 15 S 141 11 23 E	Foraminifera	Tertiary	Tertiary sediment	Rexilius, 1984b
Surface	Victorian highlands	Mainly K–Ar	Ordovician, & Devonian	Og, SDg	Richards & Singleton, 1981
Surface	Murray River Gorge	Macrofossils – echinoids	Oligo–Miocene–Pliocene	Tml, Tps	Sadler & others, 1983
Borehole	Mallee Cliffs (Murray River), N.S.W.	Foraminifera	Tertiary	Tertiary sediment	Scheibnerova, 1987
Boreholes	Teal Flat, S.A.	Foraminifera	Oligocene–Miocene	Tml, Toe	Steel, 1962
Surface	Murray River, S.A.	Macrofauna	Tertiary	Tertiary sediment	Tate, 1878
Surface	Murray River, S.A.	Macrofauna	Tertiary	Tertiary sediment	Tate, 1885
Borehole	Tareena/Kulearna Station, S.A.	Macrofossils	Late Miocene–Pliocene	Tpb	Tate, 1889
Quarry exposures	Stawell, Vic.	Macrofossils	Late Miocene–Pliocene	Tps	Taylor, 1875, 1876
Surface	Lake Menindee, N.S.W.	Marsupials	Pleistocene	Qdl	Tedford, 1955
Surface	Lake Menindee, N.S.W.	Marsupials	Pleistocene	Qdl	Tedford, 1967
Jerilderie 1	35 15 00 S 145 58 00 E	Palynology	Permian	Pl, Pu	Terpstra, 1963
Ivanhoe 1	32 54 11 S 144 17 51 E	Foraminifera	Early Cretaceous, Aptian	Kl	Terpstra, 1967
Borehole	Swan Reach, S.A.	Radiocarbon	Holocene	Qa – Tartangan Beds	Tindale, 1957
Boreholes	West Riverine Plain	Palynology	Tertiary	Teo, TmgTruswell, 1987	
Oakvale 1	32 59 03 S 140 54 09 E	Palynology	Oligocene–Miocene–Pliocene	Toe, Tmg, Tps	Truswell & others, 1985
Near surface	Coorong, S.A.	Radiocarbon	Holocene	Qho, Qhl	Von der Borch, 1976

Site	*Location*	*Type*	*Age*	*Unit(s)*	*Reference*
Near surface	Robe, S.A.	Amino acid racemization	Late Pleistocene	Qpb	Von der Borch & others, 1980
Surface	Eastern Vic.	K–Ar	Cainozoic	Tv, TQv	Wellman, 1974
Surface	N.S.W. highlands	K–Ar	Cainozoic	Tv, TQv	Wellman & McDougall, 1974
Surface	S.E. South Australia (Gambier Embayment)	Macrofauna – vertebrates	Cainozoic	Cainozoic sediment	Wells & Pledge, 1983
Surface	Murray River, S.A.	Marsupials	Quaternary	Rock shelters	Williams, 1980
Surface	Australia (including Murray Basin)	Mammals	Miocene–Pliocene–Pleistocene	Cainozoic sediment	Woodburne & others, 1985
Surface	Mount Gambier, S.A.	Macrofossils	Tertiary	Tertiary sediment	Woods–Tenison, 1867b

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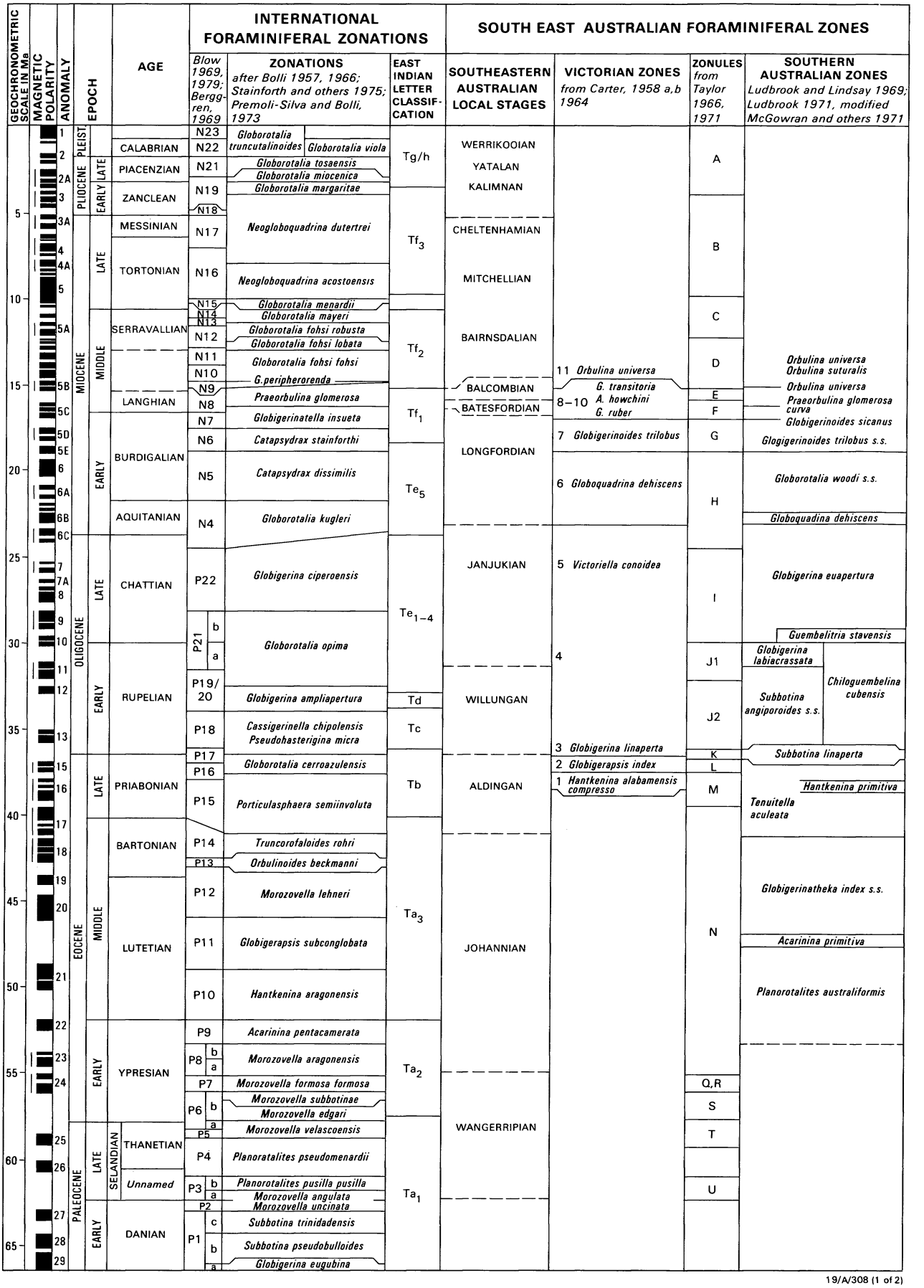
APPENDIX 5

Biostratigraphic schemes in use in the Murray Basin and adjacent areas of southeastern Australia

(based on unpublished correlation chart compiled by R. Langford, BMR)

Appendix 5



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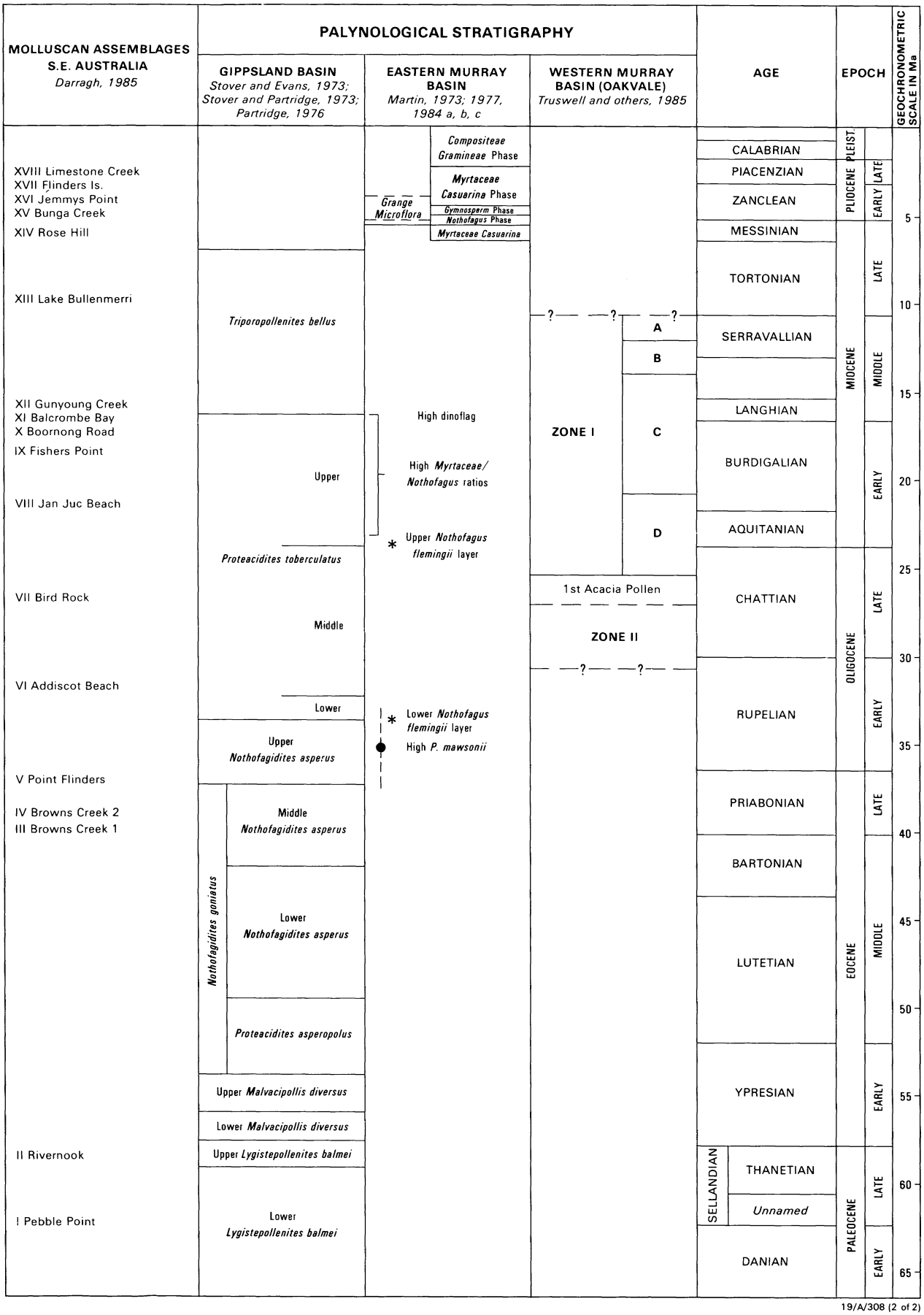
MOLLUSCAN ASSEMBLAGES S.E. AUSTRALIA
Darragh, 1985
PALYNOLOGICAL STRATIGRAPHY
GIPPSLAND BASIN
Stover and Evans, 1973; Stover and Partridge, 1973; Partridge, 1976
EASTERN MURRAY BASIN
Martin, 1973; 1977, 1984 a, b, c
WESTERN MURRAY BASIN (OAKVALE)
Truswell and others, 1985
AGE
EPOCH
GEOCHRONOMETRIC SCALE IN Ma
XVIII Limestone Creek
XVII Flinders Is.
XVI Jemmys Point
XV Bunga Creek
XIV Rose Hill
XIII Lake Bullenmerri
XII Gunyoung Creek
XI Balcrombe Bay
X Boornong Road
IX Fishers Point
VIII Jan Juc Beach
VII Bird Rock
VI Addiscot Beach
V Point Flinders
IV Browns Creek 2
III Browns Creek 1
II Rivernook
I Pebble Point
Compositeae Gramineae Phase
Myrtaceae Casuarina Phase
Grange Microflora
Gymnosperm Phase
Nothofagus Phase
Myrtaceae Casuarina
Triporopollenites bellus
High dinoflag
High Myrtaceae/ Nothofagus ratios
Upper Nothofagus flemingii layer
Upper
Proteacidites tuberculatus
Middle
Lower
Lower Nothofagus flemingii layer
High P. mawsonii
Upper Nothofagidites asperus
Middle Nothofagidites asperus
Nothofagidites goniatus
Lower Nothofagidites asperus
Proteacidites asperopolus
Upper Malvacipollis diversus
Lower Malvacipollis diversus
Upper Lygistepollenites balmei
Lower Lygistepollenites balmei
ZONE I
A
B
C
D
1st Acacia Pollen
ZONE II
CALABRIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
SELLANDIAN
THANETIAN
Unnamed
DANIAN
PLEIST.
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
LATE
EARLY
MIDDLE
5
10
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APPENDIX 6

Macrofossils

(compiled by A.E. Stephenson)

Macrofossils

This Appendix lists the genera of macrofossils which have been described to date from Murray Basin sediments; the macrofossil lists are far from complete as many units have not been thoroughly palaeontologically studied.

The Appendix is in two parts: Part A lists fossils by Type, Genus, and Formations from which it has been recorded – fossils are grouped alphabetically; Part B lists the data under Formations, Type, and Genus. It should be noted that generic names have been compiled from original publications (listed in Appendix 4), and that the systematic taxonomy used here has not been up-dated and may differ slightly from the current usages.

The main fossil types used here are from the Phyla Arthropoda (crabs, ostracods, cirripedes), Brachiopoda (brachiopods), Chordata (fish – including shark's teeth, tetrapods), Coelenterata (corals), Echinodermata (echinoids, crinoids, starfish), Mollusca (bivalves, gastropods, scaphopods, cephalopods), Plants (calcareous algae), Polyzoa (bryozoa), Porifera (sponges), and Trace Fossils (worms i.e. mainly burrows).

Murray Basin Macrofossils – Part A

Abbreviations for formations used in Part A are: Renmark Beds (Olney Formation) – Ter; Buccleuch Beds – Teb; Ettrick Formation – Toe; Winnambool Formation – Tmw; Geera Clay – Tmg; Duddo Limestone (equivalent to a composite of the Murray Group limestones, but excluding the Cadell Marl) – Tml; Gambier Limestone (including Naracoorte Limestone) – Gambier; Mannum Formation – Mannum; Morgan Limestone (excluding Cadell Marl Lens) – Morgan; Cadell Marl Lens – Cadell; Pata Limestone – Pata; Bookpurnong Beds – Tpb; Loxton Sands (lower Parilla Sand in N.S.W. and Victoria) – Tps; Norwest Bend Formation – Tpn; Blanchetown Clay (includes Bungunnia Limestone) – Qpc; Coomandook Formation – Qpl; Bridgewater Formation – Qpb; Padthaway Formation – Qcl; Monoman Formation – Monoman; Shepparton Formation – TQs; Lunettes – Qdl; Yamba Formation – Qly; Coonambidgal Formation – Qa.

Fossil type: Calcareous algae, number of genera: 2

Genus and rock units

Lithothamnion Tml (Gambier, Morgan), Tpb, Qcl; Lithophyllum Tml

Fossil type: Bivalves, number of genera: 88

Genus and rock units

Aloidis (Notocorbula) Tmw; Ammusium Tpb; Anadara (also known as Arca) Tml (Morgan), Qpb, Qcl; Anapella Qpb; Anodontia Tpn; Anomia Tpb; Antigona Tml (Morgan, Cadell), Tpb; Arcopena Tpb; Austromytilus Qpb
Barnea Tml (Morgan), Tps; Brachyodontes Qpb
Capistrocardia Tml (Cadell); Cardita Tml (Morgan), Tpb, Tps; Carditella Tml (Cadell); Carditidae Tml (Pata), Tpb; Cardium Qpb; Chione Qpb, Qcl; Chlamys Tml (Gambier, Mannum, Morgan), Tpn; Condylocardia Tml (Morgan), Tpb; Corbula Tml (Morgan, Cadell), Tpb, Tps; Corbiculina Qpb; Crassatelites Tml (Morgan), Tpb; Crenella Tpb; Cucullaea Tml (Morgan, Cadell), Tpb; Cuna Tmg, Tml (Morgan), Tpb; Cuspidaria Tpb; Cyclocardia Tmg, Tmw, Tpb; Cylichnella Tmw
Diastoma Tpn; Diaphoromactra Qpb; Dimya Tml (Morgan, Cadell), Tpb; Donax Tpb, Tps, Tpn; Dosinea Tml (Morgan), Tpb
Eucrassatella Tpb
Gari Tpb; Glycymeris Tml (Mannum, Morgan, Cadell), Tpb, Tps, Tpn; Gryphaea Tml (Morgan), Tpb
Hinnites Tpb
Katelysia Qpb, Qcl
Leda Tml (Cadell), Tpb, Tps; Ledella Ter, Tml (Morgan), Tpb; Lentipecten Tml (Mannum); Limatula Tml (Gambier, Morgan), Tps; Limopsis Tmg, Tmw, Tml (Morgan, Cadell, Pata), Tpb, Tps; Lissarca Tmw, Tpb; Lucina Tml (Cadell)
Macoma Qpb; Mactra Tml (Morgan), Tpb, Tps, Qpb; Margaritifera Tml (Morgan), Tpb; Meretrix Tpb; Miltha Tps, Tpn; Modiolus Tml (Morgan); Monacuta Tps; Myaddra Tpb; Myadora Tpb; Mytilus Tps, Tpn, Qpb
Neocardium Tpb; Nucula Tmw, Tml (Morgan, Cadell), Tpb; Nuculana Tmg, Tmw, Tml (Mannum, Cadell, Pata), Tpb, Tps; Nuculidae Tml (Pata); Numella Tmg
Ostrea Tml (Mannum, Morgan), Tps, Tpn, Qpb, Qcl
Panopaea Tpb; Pecten Tml (Gambier, Morgan), Qpb; Perna Tml (Morgan); Pinctada Tpn; Placamen Tpb, Tps, Tpn; Placunanomia Tml (Morgan), Tpb; Poroleda Tpb; Pronucula Tmg, Tml (Cadell); Propeamussium Tpb; Psammobia Tpb
Rochefortia Tml (Gambier
Salaputium Tmw; Semiactaeon Tmw; Serripecten Tml (Gambier, Mannum, Morgan), Tpb; Solecurtis Tml (Cadell); Spondylus Tml (Gambier, Mannum, Morgan), Tpn
Tapes Qpb; Tawera Tpb, Tps; Tellina Tmg, Tml (Morgan), Qpb; Trochammina Ter
Unio Qa, Qdl, TQs
Vasticardium Tpn; Venericardita Tpb; Venus Tml (Morgan), Tpb; Verticordia Tmw, Tml (Cadell), Tpb
Zenatiopsis Tml (Cadell)

Fossil type: Brachiopods, number of genera: 7

Genus and rock units

Magadina Tml (Gambier, Mannum, Morgan); Magasella Tml (Gambier, Morgan), Tpb; Magellania Tml (Gambier, Mannum, Morgan); Murravia Tml (Gambier, Mannum, Morgan)
Terebratella Tml (Gambier, Morgan), Tpb; Terebratula Tml (Gambier); Terebratulina Tml (Gambier, Morgan), Tpb

Fossil type: Bryozoa, number of genera: 38

Genus and rock units

Adeonellopsis Tmw; Adeona Tml (Morgan)
Bipora Tml (Gambier, Morgan)
Caberea Tml (Mannum, Morgan), Tps; Catenicella Tpb, Tps; Cellaria Tml (Gambier, Mannum, Morgan), Tpb, Tps; Cellepora Tml (Gambier, Mannum, Morgan), Tpb; Claviporella Tpb; Conescharellina Tps; Crateropora Tps; Crisia Tps
Diastopora Tml (Gambier)
Entalophora Tml (Gambier), Tpb
Heteropora Tml (Morgan); Hornera Tml (Gambier, Morgan), Tpb
Idmonea Tml (Gambier, Morgan), Tpb, Tps
Leckythopora Tml (Gambier, Morgan); Lepralia Tml (Gambier, Morgan), Tpb; Lichenopora Tml (Gambier, Morgan), Tpb; Lunnites Tml (Gambier), Tpb
Macropora Tml (Gambier); Mecynoccia Tps; Membranipora Tml (Gambier); Microporella Tml (Gambier)
Nellia Tps
Otionella Tpb, Tps
Petralia Tml (Mannum); Porina Tml (Gambier, Mannum, Morgan)
Retepora Tml (Gambier, Morgan), Tpb, Tps
Schismopora Tml (Gambier, Morgan); Schizoporella Tml (Gambier, Morgan), Tpb; Selenaria Tml (Gambier, Morgan), Tpb; Smittia Tml (Gambier); Smittinella Tps; Steganoporella Tml (Gambier, Morgan); Supercytis Tps
Tessaradoma Tml (Gambier); Thalamoporella Tps

Fossil type: Cephalopods, number of genera: 3

Genus and rock units

Aturia Tml (Gambier, Mannum)
Eutrephoceras Tml (Gambier, Mannum)
Nautilus Tml (Mannum)

Fossil type: Cirripedes, number of genera: 2

Genus and rock units

Balanus Tml (Morgan), Tpb, Tps
Scapellum Tml (Morgan), Tpb

Fossil type: Corals, number of genera: 12

Genus and rock units

Bathyactis Tml (Morgan), Tpb
Conocyathis Tpb; Crabnularia Tpb

Deltocyathis Tml (Morgan), Tpb
Graphularia Tml (Morgan)
Isis Tml (Morgan)
Mopsea Tml (Gambier, Morgan), Tpb, Tps
Nolotrochus Tpb; Notophyllia Tml (Morgan), Tpb
Placotrochus Tml (Morgan)
Sphenotrochus Tml (Morgan), Tpb
Trematotrochus Tpb

Fossil type: Crabs, number of genera: 1
Genus and rock units
Loxoconcha Tml (Gambier), Tpb, Tps

Fossil type: Crinoids, number of genera: 1
Genus and rock units
Antedon Tml (Gambier, Morgan)

Fossil type: Echinoids, number of genera: 21
Genus and rock units
Arachnoides Tml (Gambier, Morgan), Tpb; Astrostoma Tpb; Australanthus Teb
Cidaris Tml (Gambier)
cf. Echinobrissus Tml (Mannum); Echinocyamus Tml (Gambier, Morgan), Tpb; Echinolampas Tml (Gambier); cf. Echinolampas Tml (Mannum); Echinoneus Tml (Gambier); Eupatagus Tml (Gambier, Mannum, Morgan)
Fibularia Tml (Gambier, Mannum, Morgan), Tpb
Goniocidaris Tml (Gambier)
Linthia Tpb; Lovenia Tml (Gambier, Mannum, Morgan), Tpb
Meoma Tml (Mannum); Monostychia Tml (Gambier, Mannum, Morgan)
Paradoxechinus Tml (Morgan); Psammechinus Tml (Gambier, Mannum, Morgan); cf. Psammechinus Tml (Mannum); Pygorhynchus Tml (Mannum)
Scutellina Tml (Gambier, Mannum)

Fossil type: Fish (incl. shark's teeth), number of genera: 16
Genus and rock units
Carcharias Ter, Tml (Mannum, Morgan, Cadell); Carcharodon Tml (Gambier, Mannum, Morgan, Cadell); Carcharhinus Tml (Cadell); Cacharoides Tml (Mannum); Chrysophrys Tml (Morgan), Tpb
Diodon Tpb
Galaeocerdo Ter, Tml (Cadell), Tpb
Hemipristis Tml (Cadell)
Isurus Ter, Tml (Gambier, Mannum, Cadell), Tpn
Lamna Ter, Tml (Gambier, Mannum, Cadell), Tps
Myliobatus Ter, Tml (Morgan), Tpb
Neoceratodus Qpc
Notidanus Ter; cf. Notidanus Tml (Mannum)
Plectroplites Qa
Trygoa Tpb

Fossil type: Gastropods, number of genera: 88
Genus and rock units
Alcithoe Tml (Gambier); Ancilla Tml (Morgan), Tpb; Argobuccinum Tml (Cadell); Astralium Qpb; Ataxocerithium Tmw; Austrotriton Tml (Morgan, Cadell)
Bela Tml (Morgan); Bellastraea Qpb; Bittium Qpb; Brookula Tmg, Tmw; Buchozia Tmw; Bullaria Qpb
Calliostomo Tmw; Calyptraea Tml (Morgan), Tpb, Tps; Capulus Qpb; Cassis Tml (Mannum), Tpb; Catharidus Qpb; Cerithiella Tmw; Cerithiopsis Tmg; Cerithium Tml (Morgan), Tpb; Clanculus Tpb, Qpb; Cirsotrema Tmw; Collonia Tmg; Cominella Qpb; Conomitra Tmw; Conus Qpb; Corbiculina Qcl, Qa; Coxiella Qpb, Qcl, Qpc, Qly; Cyclostrema Tpb; Cypraea Tml (Gambier, Mannum, Morgan)
Eglisia Tml (Morgan), Tpb; Eotrigonia Tml (Morgan); Erycina Tml (Morgan), Tpb; Euchelus Tpb; Eulima Tpb; Eumarginula Tps
Fasciolaria Tml (Morgan, Cadell), Tpb, Qpb; Filodrillia Tmw; Fusus Tml (Cadell); Fusinus Qpb
Guraleus Tmw
Haliotus Qpb; Hartungia Qpl; Hexaplex Tmw; Hinia Tmg, Tmw; Homalina Qpb
Isoclanculus Qpb
Lenameria Qpb, Qcl, Qa; Leiopyrga Tml (Morgan), Tpb, Tps, Tpn; Limnea Qcl, Qa; Liotina Tmg; Lotorium Tml (Morgan), Tpb
Marginella Tmw, Tml (Morgan), Tpb, Tps; Monodonta Qpb; Murex Tml (Cadell)
Nacella Qpb; Nassa Tml (Cadell), Tpb; Nassarius Tmw, Qpb; Natica Tml (Morgan), Tpb, Tps; Neotrigonia Tpb, Tps, Tpn; Niso Tml (Morgan); Notospisula Qpb
Obtortio Tmw; Onoba Tpb
Pancanassa Qpb; Parastrophia Tmg; Peristernia Tml (Cadell); Personella Tmw; Phasianella Qpb; Planorbis Qpb; Pleuromeris Tmg, Tml (Morgan), Tpb, Tps; Pleurotoma Tml (Morgan), Tpb; Polynices Qpb; Pulria Qpb; Pyrene Qpb; Pyrimidella Tpb, Tps Rissoa Tml (Morgan), Tpb
Semicassis Tml (Morgan); Sphaeronova Qpb, Qcl, Qa; Syrnola Tmg, Tps
Tatea Qpb; Teinostoma Tpb; Terebra Tml (Morgan), Tpb; Tornatina Tpb; Triforis Tmw; Trigonia Tml (Morgan), Tpb; Triton Tml (Cadell); Trophon Tml (Cadell); Tudicla Tml (Morgan), Tpb; Turbo Qpb; Turritella Ter, Teb, Tmg, Tmw, Tml (Gambier, Morgan, Cadell, Pata), Tpb; Tylospira Tml (Morgan), Tpb
Vaginella Tml (Morgan); Voluta Tml (Morgan); Volutospina Tml (Cadell); Volvulella Tpb, Tps
Zeacumantus Qpb; Zemira Tml (Morgan)

Fossil type: Ostracods, number of genera: 19
Genus and rock units
Argilloecia Tml (Morgan); Atalacythere Tmw
Bairdia Tml (Gambier, Morgan), Tpb; Bythocypris Tml (Gambier, Morgan0, Tpb
Candona Qpc; Candoncypris Qpc; Cypretta Qpc; Cypridopsis Qpc; Cypris Qpc; Cythere Tml (Gambier, Morgan), Tpb, Tps; Cytherella Tml (Gambier, Morgan), Tpb, Tps; Cytherelloidea Tmw; Cytheropteron Tml (Morgan), Tpb; Cytherula Tpb
Diacypris Qpc
Iyocypris Qpc
Krithe Tmw
Macrocypris Tml (Gambier, Morgan), Tpb, Tps
Xestoleberis Tml (Morgan), Tpb

Fossil type: Scaphopods, number of genera: 3
Genus and rock units
Cadulus Tpb
Dentalium Ter, Tmw, Tml (Mannum, Morgan, Cadell, Pata), Tpb, Tps, Tpn
Entalis Tml (Cadell)

Fossil type: Sponges, number of genera: 1
Genus and rock units
Ecionema Tmw

Fossil type: Starfish, number of genera: 2
Genus and rock units
Clypeaster Tml (Morgan), Tpb
Pentagonaster Tml (Gambier, Morgan), Tpb

Fossil type: Tetrapods, number of genera: 7
Genus and rock units
Diprotodon TQs, Qdl
Homo TQs, Qdl, Qa
Macropus TQs, Qdl
Nototherium Monoman
'Penguin bones' Tml (Gambier); Phascolarctos TQs, Qdl
Thylacoleo TQs, Qdl

Fossil type: Trace Fossils (worms), number of genera: 4
Genus and rock units
Ditrupa Tml (Gambier, Morgan, Pata), Tpb, Tps
Sepula Tml (Gambier, Morgan); Spirobis Tml (Gambier)
Vermes Tml (Morgan)

Murray Basin macrofossils — Part B

Units: Blanchetown Clay and Bungunnia Limestone
Age: Late Pliocene-Late Pleistocene (BC), Late Pleistocene (BL)
Data quality: poor; little work has been done on fauna of Blanchetown Clay and Bungunnia Limestone, and former unit is usually heavily oxidised, destroying most fossils; fauna is dominated by ostracods.
Fish: 1 genus — Neoceratodus (Blanchetown Clay)
Gastropods: 1 genus — Coxiella (Bungunnia Limestone)
Ostracods: 7 genera — Candona (Bungunnia Limestone), Candoncypris (Blanchetown Clay), Cypretta (Blanchetown Clay), Cypridopsis (Bungunnia Limestone), Cypris (Bungunnia Limestone), Diacypris (Blanchetown Clay), Iyocypris (Blanchetown Clay)
Others: worm tubes have been recorded from Blanchetown Clay, and algal structures are common in Bungunnia Limestone.

Unit: Bookpurnong Beds
Age: Late Miocene to Early Pliocene
Data quality: very good; although Bookpurnong Beds are almost entirely subsurface, they have been intersected by numerous boreholes, and macrofauna has been well described; environment of deposition has also aided fossil preservation; Bookpurnong

Beds have a diverse shallow marine fauna, dominated by bivalves, gastropods, and bryozoa.
Calcareous algae: 1 genus — Lithothamnion
Brachiopods: 3 genera — Magasella, Terebratella, Terebratulina
Bivalves: 43 genera — Ammusium, Anomia, Antigona, Arcoperna, Cardita, Carditae, Condylocardia, Corbula, Crassatelites, Crenella, Cucullaea, Cuna, Cuspidaria, Cyclocardia, Dimya, Donax, Dosinea, Eucrassatella, Gari, Glycymeris, Gryphaea, Hinnites, Leda, Ledella, Limopsis, Lissarca, Mactra, Margaritifera, Meretrix, Myaddra, Neocardium, Nucula, Nuculana, Panopaea, Placamen, Placunanomia, Poroleda, Propeamussium, Psammobia, Serripecten, Tawera, Venus, Venericardita
Bryozoa: 15 genera — Bipora, Catenicella, Cellaria, Cellepora, Claviporella, Entalophora, Hornera, Idmonea, Lepralia, Lichenopora, Lunulites, Otionella, Retepora, Schizoporella, Selenaria
Cirripedes: 2 genera — , Balanus, Scapellum
Corals: 9 genera — Bathyactis, Conocyathus, Deltocyathus, Graphularia, Holotrochus, Mopsea, Notophyllia, Sphenotrochus, Trematotrochus
Crabs: 1 genus — Loxoconcha
Crinoids: 1 genus — Antedon
Echinoids: 6 genera — Arachnoides, Astrostoma, Echinocyamus, Fibularia, Linthia, Lovenia
Fish: 5 genera — Chryophrys, Diodon, Galaeocerdo, Myliobatus, Trygoa
Gastropods: 30 genera — Ancilla, Calyptraea, Cassis, Cerithium, Clanculus, Cyclostrema, Eglisia, Erycina, Euchelus, Eulima, Fasciolaria, Leiopyrga, Lotorium, Marginella, Nassa, Natica, Neotrigonia, Onoba, Pleuromeris, Pleurotoma, Pryamidella, Rissoa, Teinostoma, Terebra, Tornatina, Trigonia, Tudicla, Turritella, Tylospira, Volvulella
Ostracods: 8 genera — Bairdia, Bythocypris, Cythere, Cytherella, Cytherula, Cytheropteron, Macrocypris, Xestoleberis
Scaphopods: 2 genera — Cadulus, Dentalium
Sponges: 'spicules' recorded
Starfish: 2 genera — Clypeaster, Pentagonaster
Trace Fossils: 1 genus — Ditrupa (worm)

Unit: Bridgewater Formation
Age: Late Pleistocene
Data quality: poor; Bridgewater Formation forms beach ridge complexes in both Murray and Otway Basins, but fauna is poorly described; information below includes only bivalves and gastropods, and is based on Tindale (1933) and Blackburn (1966a); and taxonomy from former source in particular may be out of date.
Bivalves: 16 genera — Anadara, Anapella, Austromytilus, Brachyodontes, Cardium, Chione, Corbiculina, Diaphoromactra, Katelysia, Macoma, Mactra, Mytilus, Ostrea, Pecten, Tapes, Tellina
Gastropods: 30 genera — Astralium, Bellastraea, Bittium, Bullaria, Capulus, Catharidus, Clanculus, Cominella, Conus, Coxiella, Fasciolaria, Fusinus, Haliotus, Homalina, Isoclanculus, Lenameria, Monodonta, Nacella, Nassarius, Notospisula, Pancanassa, Phasianella, Planorbis, Polynices, Pulria, Pyrene, Sphaeronova, Tatea, Turbo, Zeacumantus

Unit: Buccleuch beds
Age: Late Eocene
Data quality: very poor; Buccleuch Beds are entirely subsurface, and their macrofauna has not been thoroughly described; Buccleuch Bed A is most fossiliferous of three Beds. All information is from Ludbrook (1957, 1961a).
Bryozoa: 'abundant', particularly in Bed A
Echinoids: 1 genus — Australanthus
Fish: Unidentified shark's teeth have been noted
Gastropods: 1 genus — Turritella

Unit: Bunyip Sand
Age: Holocene
Data quality: very poor; only 'fossiliferous' material recorded from Bunyip Sand is shell fragments in Aboriginal middens, in addition to marsupial bones; environment of deposition does not favour fossil preservation.

Unit: Cadell Marl Lens
Age: Early Miocene
Data quality: good; although bryozoa present have not been described; Cadell Marl Lens is richly fossiliferous, with a macrofauna dominated by gastropods and bivalves. Although it is mainly a subsurface unit, Cadell Marl Lens crops out in cliffs of Murray River, and mollusc fauna has been described by Tate (1885) and Ludbrook (1957, 1961a).
Bivalves: 17 genera — Antigona, Capistrocardia, Carditella, Corbula, Cucullaea, Dimya, Glycymeris, Leda, Limopsis, Lucina, Myadora, Nucula, Nuculana, Pronucula, Solecurtis, Verticordia, Zenaiopsis
Bryozoa: 'present'
Fish: 7 genera — Carcharhinus, Carcharius, Carcharodon, Galeaocerdo, Hemipristis, Isurus, Lamna
Gastropods: 11 genera — Argobuccinum, Austrotriton, Fasciolaria, Fusus, Murex, Nassa, Peristernia, Triton, Turritella, Trophon, Volutospina
Scaphopods: 2 genera — Dentalium, Entalis

Unit: Calcretes
Age: Early Pleistocene to Holocene
Data quality: nil; no macrofossil remains have been recorded from any of Murray Basin calcretes; diagenetic processes which form calcretes would actively act to destroy calcareous hard parts. Calcrete rhyzoliths commonly contain internal moulds of plant roots around which they were formed.

Unit: Calivil Formation
Age: Pliocene
Data quality: nil; Calivil Formation is mainly concealed, and no macrofossils have been recorded from it; environment of deposition of this unit makes fossil preservation unlikely.

Unit: Compton Conglomerate
Age: Oligocene
Data quality: very poor; Compton Conglomerate is almost entirely subsurface, and no macrofauna has been described, although Ludbrook (1961a) notes presence locally of 'fragments of brachiopod shells and bryozoa'.

Unit: Coomandook Formation
Age: Early Pleistocene
Data quality: very poor; Coomandook Formation almost entirely subsurface, and is dominated palaeontologically by reworked skeletal material from Murray Group limestones. Ludbrook (1978) noted but did not describe "a comparatively sparse contemporary fossil assemblage".
Gastropods: 1 genus — Hartungia

Unit: Coonambidgal Formation (see Shepparton Formation)

Unit: Coorong lagoonal dolomites
Age: Holocene
Data quality: modern zoological literature is excellent, palaeontological literature is non-existent. Coorong Lagoon is inhabited by a modern restricted marine fauna, decreasing in diversity towards more extreme environments in south. Gastropods, bivalves, foraminifera, ostracods, fish, and algae are common in northern lagoon; all these forms except bivalves are also present in southern lagoon, although with reduced diversity.

Unit: Duddo Limestone
Age: Late Oligocene to Middle Miocene
Data quality: excellent; Duddo Limestone in New South Wales and Victoria is equivalent to following combined South Australian units: Gambier Limestone, Mannum Formation, Morgan Limestone, and Pata Limestone. Data from these units have been added to that from Duddo Limestone itself in lists below; however, data from Naracoorte Limestone, Finniss Clay, and Cadell Marl Lens have not been included.
Calcareous algae: 2 genera — Lithophyllum, Lithothamnion
Bivalves: 35 genera — Anadara (also known as Arca), Antigona, Barnea, Cardita, Carditidae, Chlamys, Condylocardia, Corbula, Crassatellites, Cucullaea, Cuna, Dimya, Dosinea, Glycymeris, Gryphaea, Ledella, Lentipecten, Limatula, Limopsis, Mactra, Margaritifera, Modiolus, Myadora, Nucula, Nuculana, Nuculidae, Ostrea, Pecten, Perna, Placunanomia, Rochefortia, Serripecten, Spondylus, Tellina, Venus
Brachiopods: 7 genera — Magadina, Magellania, Magasella, Murravia, Terebratella, Terebratula, Terebratulina
Bryozoa: 26 genera — Adeona, Bipora, Caberea, Cellaria, Cellepora, Diastopora, Entalophora, Heteropora, Hornera, Idmonea, Leckythopora, Lepralia, Lichenopora, Lunnites, Macropora, Membranipora, Microporella, Petralia, Porina, Retepora, Schismopora, Selenaria, Schizoporella, Smittia, Steganoporella, Tessaradoma
Chephalopods: 3 genera — Aturia, Eutrephoceras, Nautilus
Cirripedes: 2 genera — Balanus, Scapellum
Corals: 8 genera — Bathyactis, Deltocyathus, Graphularia, Isis, Mopsea, Notophyllia, Placotrochus, Sphenotrochus
Crabs: 1 genus — Loxoconcha
Crinoids: 1 genus — Antedon
Echinoids: 18 genera — Arachnoides, Cidaris, cf. Echinobrissus, Echinocyamus, Echinolampas, cf. Echinolampas, Echinoneus, Eupatagus, Fibularia, Goniocidaris, Lovenia, Meoma, Monostylina, Paradoxechinus, Psammechinus, cf. Psammechinus, Pygorhynchus, Scutellina
Fish: 10 genera — Carcharias, Carcharodon, Carcharoides, Chrysophrys, Galeaocerdo, Isurus, Lamna, Myliobatus, cf. Notidanus
Gastropods: 28 genera — Alcithoe, Ancilla, Austrotriton, Bela, Calyptraea, Cassis, Cerithium, Cypraea, Eglisia, Erycina,

Fasciolaria, Leiopyrga, Lotorium, Marginella, Natica, Niso, Pleuromeris, Pleurotoma, Rissoa, Semicassis, Terebra, Trigonia, Tudicla, Turritella, Tylospira, Vaginella, Voluta, Zemira
Ostracods: 8 genera – Argilloecia, Bairdia, Bythocypris, Cythere, Cytherella, Cytheropteron, Macrocypris, Xestoleberis
Scaphopods: 1 genus – Dentalium
Starfish: 2 genera – Clypeaster, Pentagonaster
Trace Fossils: 4 genera (worms) – Ditrupa, Sepula, Spirobis, Vermes

Unit: Ettrick Formation
Age: Late Oligocene
Data quality: very poor; Ettrick Formation is almost entirely subsurface, and although its microfauna is well known, macrofauna has not been described in any detail. Ludbrook (1961a) recorded bivalves, byrozoa, echinoids, fish teeth, and gastropods from Ettrick Formation, but did not identify genera.

Unit: Finniss Clay
Age: Early Miocene
Data quality: nil; no macrofossils have been recorded from Finniss Clay, although Ludbrook (1961a) described an impoverished marine microfauna.

Unit: Gambier Limestone (including Naracoorte Limestone)
Age: Late Oligocene to Early Miocene (although Naracoorte Limestone ranges from Early Miocene to Middle Miocene).
Data quality: good to poor; where Gambier Limestone is subsurface few macrofossils have been recorded, but in south where its upper member (Naracoorte Limestone) crops out palaeontological control is good.
Calcareous algae: 1 genus – Lithothamnion
Bivalves: 6 genera – Chlamys, Limatula, Pecten, Rochefortia, Serripecten, Spondylus
Brachiopods: 7 genera – Magadina, Magasella, Magellania, Murravia, Terebratella, Terebratula, Terebratulina
Bryozoa: 21 genera – Bipora, Cellaria, Cellepora, Diastopora, Entalophora, Hornera, Idmonea, Leckythopora, Lepralia, Lichenopora, Lunnites, Macropora, Membranipora, Microporella, Porina, Retepora, Schismopora, Schizoporella, Smittia, Steganoporella, Tessaradoma
Chephalopods: 2 genera – Aturia, Eutrephoceras
Corals: 1 genus – Mopsea
Crabs: 1 genus – Loxoconcha
Crinoids: 1 genus – Antedon
Echinoids: 12 genera – Arachnoides Cidaris, Echinocyamus, Echinolampas, Echinoneus, Eupatagus, Fibularia, Goniocidaris, Lovenia, Monostylina, Psammechinus, Scutellina
Fish: 3 genera – Carcharodon, Isurus, Lamna
Gastropods: 3 genera – Alcithoe, Cypraea, Turritella
Ostracods: 6 genera – Bairdia, Bythocypris, Cythere, Cytherella, Cytheropteron, Macrocypris
Sponges: spicules present
Tetrapods: 'penguin bones' were recorded by Ludbrook (1961a)
Trace Fossils: 3 genera (worms) – Ditrupa, Sepula, Spirobis

Unit: Geera Clay
Age: Late Oligocene to Middle Miocene
Data quality: poor; Geera Clay is entirely subsurface, and has only a sparse macrofauna owing to environment in which it was deposited; bryozoans which are ubiquitous in other marine Miocene formations of Murray Basin are absent from Geera Clay (Lawrence, 1966).
Bivalves: 7 genera – Cuna, Cyclocardia, Limopsis, Nuculana, Numella, Pronucula, Tellina
Corals: 'present'
Gastropods: 9 genera – Brookula, Cerithiopsis, Collonia, Hinia, Liotina, Parastrophia, Pleuromeris, Syrnola, Turritella
Ostracods: 'present'

Unit: Laterites
Age: Late Tertiary to Quaternary
Data quality: nil; no macrofossils have been recorded from any laterite deposits in Murray Basin. This is probably because process of laterisation is extremely inimical to fossil preservation.

Unit: Lowan Sand (see Molineaux Sand)

Units: Loxton Sands and Parilla Sand
Age: Early Pliocene
Data quality: excellent; these units are well exposed in outcrop, but only Loxton Sands in South Australia and lower part of Parilla Sand in New South Wales and Victoria are fossiliferous (although authors of this Bulletin have seen worm tubes in upper Parilla Sand near Pooncarie).
Bivalves: 17 genera – Barnea, Cardita, Corbula, Cucullaea, Donax, Glycymeris, Leda, Limatula, Limopsis, Mactra, Miltha, Monacuta, Mytilus, Nuculana, Ostrea, Placamen, Tawera
Bryozoa: 14 genera (but some possibly reworked) – Caberea, Catenicella, Cellaria, Conescharellina, Cratenopora, Crisia, Idmonea, Mecynoccia, Nellia, Otionella, Retepora, Smittinella, Supercytis, Thalamoporella
Cirripedes: 1 genus – Balanus
Corals: 1 genus – Mopsea
Crabs: 1 genus – Loxoconcha
Echinoids: 'spines'
Fish: 1 genus – Lamna
Gastropods: 11 genera – Calyptraea, Erycina, Eumarginula, Leiopyrga, Marginella, Natica, Neotrigonia, Pleuromeris, Pyramidella, Syrnola, Volvulella
Ostracods: 3 genera – Cythere, Cytherella, Macrocypris
Scaphopods: 1 genus – Dentalium
Trace Fossils: 1 genus (worm), plus other burrows – Ditrupa

Unit: Lunettes (see Shepparton Formation)

Unit: Mannum Formation
Age: Early Miocene
Data quality: very good; Mannum Formation crops out in cliffs of lower Murray River gorge, and has been well studied, although it does not contain as diverse a macrofauna as overlying Morgan Limestone.
Bivalves: 7 genera – Chlamys, Glycymeris, Lentipecten, Nuculana, Ostrea, Serripecten, Spondylus
Brachiopods: 3 genera – Magadina, Magellania, Murravia
Bryozoa: 6 genera – Caberea, Cellaria, Cellepora, Petralia, Porina, Selenaria
Chephalopods: 3 genera – Aturia, Eutrephoceras, Nautilus
Echinoids: 11 genera – cf. Echinobrissus, cf. Echinolampas, Eupatagus, Fibularia, Lovenia, Meoma, Monostychia, Psammechinus, cf., Psammechinus, Pygorhynchus, Scutellina
Fish: 6 genera – Carcharia, Carcharodon, Carcharoides, Isurus, Lamna, cf. Notidanus
Gastropods: 2 genera – Cassis , Cypraea
Scaphopods: 1 genus – Dentalium

Units: Molineaux Sand and Lowan Sand
Age: Holocene
Data quality: nil; Molineaux Sand (South Australia) and Lowan Sand (Victoria) contain some Aboriginal artifacts, but no fauna has been described from these mobile dunefields.

Unit: Monoman Formation (see Shepparton Formation)

Unit: Morgan Limestone
Age: Early to Middle Miocene
Data quality: excellent; Morgan Limestone is well exposed in cliffs of Murray River gorge, and is also known from several thousand boreholes. Morgan Limestone has a very diverse macrofauna dominated by bivalves, gastropods, bryzoa, and echinoids; middle member of Morgan Limestone, Cadell Marl Lens, has a quite distinct fauna and its palaeontology is described in this Appendix in its own right.
Calcareous algae: 1 genus – Lithothamnion
Bivalves: 30 genera – Anadara (also known as Arca)Antigona, Barnea, Cardita, Chlamys, Condylocardia, Corbula, Crassatellites, Cucullaea Cuna, Dimya, Dosinea, Glycymeris, Gryphaea, Ledella, Limatula, Limopsis, Mactra, Margaritifera, Modiolus Myadora, Nucula, Ostrea, Pecten, Perna Placunanomia, Serripecten, Spondylus, Tellina, Venus
Brachiopods: 6 genera – Magadina, Magasella, Magellania, Murravia, Terebratella, Terebratulina
Bryozoa: 17 genera (including 2 possibly reworked) – Adeona, Bipora, Caberea, Cellaria, Cellepora, Heteropora, Hornera, Idmonea, Leckythopora (possibly reworked), Lepralia, Lichenopora, Porina, Retepora, Schismopora, Schizoporella, Selenaria, Steganoporella (possibly reworked)
Cirripedes: 2 genera – Balanus, Scapellum
Corals: 8 genera – Bathyactis, Deltocyathus, Graphularia, Isis, Mopsea, Notophyllia, Placotrochus, Sphenotrochus
Crinoids: 1 genus – Antedon
Echinoids: 8 genera (including 1 possibly reworked) – Arachnoides, Echinocyamus, Eupatagus, Fibularia, Lovenia, Monostylina, Paradoxechinus, (possibly reworked), Psammechinus
Fish: 4 genera, Carcharias, Carcharodon, Chrysophrys, Myliobatus
Gastropods: 27 genera – Ancilla, Austrotriton, Bela, Calyptraea, Cerithium, Cypraea, Eglisia, Eotrigonia, Erycina, Fasciolaria, Leiopyrga, Lotorium, Marginella, Natica, Niso, Pleuromeris, Pleurotoma, Rissoa, Semicassis, Terebra, Trigonia, Tudicla, Turritella, Tylospira, Vaginella, Voluta, Zemira
Ostracods: 8 genera – Argilloecia, Bairdia, Bythocypris, Cythere, Cytherella, Cytheropteron, Macrocypris, Xestoleberis
Scaphopods: 1 genus – Dentalium
Starfish: 2 genera – Clypeaster, Pentagonaster
Trace Fossils: 3 genera (worms) – Ditrupa, Sepula, Vermes

Unit: Norwest Bend Formation
Age: Pliocene
Data quality: fair; Norwest Bend Formation is well exposed in outcrop, but many of macrofossils present have not been

systematically identified; formation is totally dominated by oyster shells, and other macrofossils form only a tiny percentage of preserved biota.
Bivalves: 11 genera – Anodontia, Chlamys, Donax, Glycymeris, Miltha, Mytilus, Ostrea, Pinctada, Placamen, Spondylus, Vasticardium
Bryozoa: encrusting forms are present on many oysters
Corals: present, but rare
Echinoids: spines present
Fish: 1 genus, Isurus
Gastropods: 3 genera – Diastoma, Leiopyrga, Neotrigonia
Scaphopods: 1 genus – Dentalium

Unit: Olney Formation (see Renmark beds)

Units: Padthaway Formation and Qpu unnamed dolomites
Age: Late Pleistocene
Data quality: very poor; no detailed palaeontological study has been undertaken on either of these units; lagoonal Qpu dolomites have abundant algal structures, but no macrofossils have been recorded. Padthaway Formation contains both marine and freshwater molluscs (as below). All information is from Sprigg (1952a) or Cook & others (1977).
Bivalves: 4 genera (all marine) – Anadara, Chione, Katelysia, Ostrea
Gastropods: 5 genera – Corbiculina (fresh-water), Coxiella (saline water or, restricted marine), Lenameria, Limnea, Sphaerinova

Unit: Parilla Sand (see Loxton Sands)

Unit: Pata Limestone
Age: Middle Miocene
Data quality: poor; until recently Pata Limestone was recognised only in subsurface; macrofauna of Pata Limestone is poorly known, although some forms described as being from underlying Morgan Limestone may in fact have been located in younger formation.
Bivalves: 4 genera – Carditidae, Limopsis, Nuculana, Nuculidae
Bryozoa: present but not described
Gastropods: 1 genus, Turritella
Ostracods: present
Scaphopods: 1 genus – Dentalium
Trace Fossils: 1 genus (worm) – Ditrupa

Unit: Pooraka Formation and other colluvium (Qfr)
Age: Late Pleistocene (Pooraka); Tertiary to Holocene (Qfr)
Data quality: nil; environment of deposition of these colluvial units makes macrofossil preservation unlikely, and none have yet been recorded.

Unit: Qdp sand plain unit
Age: Late Pleistocene
Data quality: nil; no macrofossils have been recorded from this aeolian unit.

Unit: Qdu dunes (see Woorinen Formation)

Unit: Qpu lagoonal dolomites (see Padthaway Formation)

Units: Renmark beds, Warina Sand, and Olney Formation
Age: Palaeocene to Eocene (Renmark), Paleocene (Warina), and Eocene to Middle Miocene (Olney)
Data quality: very poor; these formations are partly synonymous, and all are entirely subsurface; only macrofossils known are from thin, marine uppermost part of Olney Formation; fluvio-lacustrine parts of these units contain numerous coals, but macrofossils have not yet been recovered from dominant non-marine section.
Bivalves: 2 genera – Ledella, Trochammina
Corals: present
Fish: 6 genera – Carcharias, Galeocerdo, Isurus, Lamna, Myliobatus, Notidanus
Gastropods: 1 genus – Turritella
Scaphopods: 1 genus – Dentalium

Unit: Semaphore Sand
Age: Holocene
Data quality: not relevant; Semaphore Sand is modern beach-dune complex of Murray Basin; whilst an abundance of shelly material is present in and on beach and lower part of dune complex, these can not be considered to be true fossils; Semaphore Sand locally contains Aboriginal shell middens.

Units: Shepparton Formation, Monoman Formation, Lunettes, and Coonambidgal Formation and other Late Quaternary alluvium and lake sediments
Age: Pliocene to Late Pleistocene (Shepparton), Late Pleistocene (Monoman), Late Pleistocene to Holocene (lunettes), Holocene (Coonambidgal)
Data quality: very poor; these formations are described together, because actual unit containing Quaternary fossils is unclear in much literature. Coonambidgal Formation includes modern sediments of Murray and Darling Rivers, which harbor a well described macrofauna. However, little fossil material has been recorded from either this unit or older Shepparton Formation, with exception of that from archaeological 'digs', which has a strong bias towards human and other tetrapod remains. Similarly, material from lunettes is largely but not entirely from Aboriginal middens. Monoman Formation is a very local fluvial unit in South Australia.
Bivalves: 1 genus – Unio (Coonambidgal Formation)
Fish: 1 genus – Plectroplites (Coonambidgal Formation)
Tetrapods: 6 genera – Diprotodon (Shepparton Formation, lunettes), Homo (Shepparton Formation, lunettes, Coonambidgal Formation), Macropus (Shepparton Formation, lunettes), Nototherium (Monoman Formation), Phascolarctos (Shepparton Formation, lunettes), Thylacoleo (Shepparton Formation, lunettes)

Unit: Source-bordering dunes
Age: Pliocene to Holocene
Data quality: nil; no macrofossils have been recorded from these aeolian features of Riverine Plain.

Unit: St. Kilds Formation
Age: Holocene
Data quality: nil; St Kilda Formation contains shell banks of Holocene organisms, but these have not been studied in any palaeontological detail.

Unit: Warina Sand (see Renmark beds)

Unit: Winnambool Formation
Age: Late Oligocene to Middle Miocene
Data quality: poor; although there has been some limited study of Winnambool Formation, it is entirely subsurface, and major taxa such as bryozoa have not been adequately described.
Bivalves: 10 genera – Aloidis (Notocorbula), Cylichnella, Cyclocardia, Limopsis, Lissarca, Nucula, Nuculana, Salaputium, Semiactaeon, Verticordia
Bryozoa: 1 genus identified, but bryozoa in general 'common' – Adeonellopsis
Gastropods: 17 genera – Ataxocerithium, Brookula, Buchozia, Calliostomo, Cerithiella, Cirsotrema, Conomitra, Filodrillia, Guraleus, Hexaplex, Hinia, Marginella, Nassarius, Obtorti, Personella, Triforis, Turritella
Ostracods: 6 genera – Atalacythere, Bythocypris, Cythere, Cytherella, Cytherelloidea, Krithe
Scaphopods: 1 genus – Dentalium
Sponges: 1 genus – Ecionema
Trace Fossils: worms present

Units: Woorinen Formation and reworked Woorinen dunes Qdu
Age: Late Pleistocene (Woorinen); Late Pleistocene to Holocene (Qdu)
Data quality: nil; no macrofossils have yet been recorded from these aeolian units.

Unit: Yamba Formation
Age: Late Pleistocene to Holocene
Data quality: poor; highly saline environment of deposition of Yamba Formation is inimical to most lifeforms, and only one macrofossil taxon has been recorded from this formation.
Gastropods: 1 genus – Coxiella

GEOLOGY OF THE MURRAY BASIN
SOUTH EASTERN AUSTRALIA

by C.M. BROWN and A.E. STEPHENSON

1991

SCALE 1:1 000 000

0 20 40 60 80 100 KILOMETRES

Lambert Conformal Conic Projection with Standard Parallels 32°00'S and 37°00'S

AUSTRALIA

		LITHOLOGY	DEPOSITIONAL ENVIRONMENTS	GEOMORPHIC EXPRESSION
QUATERNARY	HOLOCENE	**Hsk** St. Kilda Formation: unconsolidated mud, silt, sand, shell debris; minor salt crusts of gypsum, halite	estuarine, coastal lake and swamp	forms littoral lake complexes; partly emergent estuarine flats and valleys
		Hm Unconsolidated to weakly lithified, fossiliferous, marine and dolomitic mud, dolomitic, minor quartz sand, clay; shell detritus, calcareous algal laminites	restricted, brackish to marine, lagoonal	locally exposed around margins of the Coorong and other coastal lake complexes
		Hse Seemaphore Sand: unconsolidated, locally mobile, white, calcareous, fossiliferous quartz sand; minor humic debris, calcareous rhizoliths	coastal beach and associated aeolian dune	forms present-day coastal beach and dome complexes
		Hc Coonambidgal Formation and other alluvial deposits: unconsolidated, grey, brown, micaceous silty clay, silt, palaeolithic sand, gravel	fluvial, fluvio-lacustrine, channel and floodplain environments of existing rivers	estuary in narrow meander belts; anastomosed distributaries and confined floodplains incised within Holocene and Pleistocene landscapes and in tributary highland valleys
		Hdb Bunyip Sand: unconsolidated, locally mobile, pale red-brown quartz sand; minor calcareous rhizoliths	fluvial-derived, source bordering, aeolian dune	forms elongate dunefields east of River Murray in South Australia
		Hwd Unconsolidated, locally mobile, pale orange, yellow, siliceous sand; locally includes abundant micaceous and lithic grains	fluvial-derived, source bordering, aeolian dune	forms elliptical mounds and elongate hummocky dune complexes adjacent to active and former river channels
	LATE PLEISTOCENE TO HOLOCENE	**Qdm** Molineaux–Lowan Sands: unconsolidated, locally mobile, yellow, grey, pale orange, well-sorted, medium to fine, fluvial quartz sand in southernmost Lindsay–Mallee–Wimmera; aeolian-derived, palaeolithic; other components variously modified by pedogenesis; contains minor calcareous, filamental rhizoliths; calcrete glaebules; rare cemented pisolith	aeolian dune	forms irregular to sub-parabolic, locally linear, sharp-crested, densely vegetated dunes with narrow, interdune corridors; and minor sand plains; forms extensive, narrowly trending, tongue-like dunefields
		Qdl Unconsolidated, locally mobile, red-brown, pale orange, siliceous sand; consists of medium to fine quartz grains, admixed with humic debris; fragmented calcareous and gypsiferous filamental rhizoliths; variously modified by pedogenesis	aeolian dune	forms sharp-crested, irregular to sub-parabolic, locally linear dunes; and minor sand plains; forms extensive, subparallel, narrow, crescentic trending dunefields
		Ql Friable to plastic, finely laminated, grey–olive, silty clay; humic clay; grey palaeosols; locally includes medium to fine sand	lacustrine and associated streamline environments	occurs in floodplain lakes and swamps, interdune deflation hollows, and coastal lake complexes
		Qcy Yamba Formation and other saline lake deposits: friable, pale grey gypsite, gypsiferous clay with calcrete crystoid; grey–yellow gypsum–quartz sand aggregates; locally includes grey clay with crystalline gypsum mush, cinder-like sulphide-rich mud; with ephemeral salt crusts of gypsum, halite, thenardite, mirabilite; in places associated with mounds and sheets of ferricrete, calcrete and dolcrete cemented quartz sand	lacustrine, evaporitic and aeolian environments of ephemerally active playas, maintained by groundwater discharge and by deflation of lake floors	forms aeolian-modified gypsite flats; active salinas; occur in topographic lows on irregularly shaped lake complexes entrenched within relict pedocrete of former lake floors
		Qdd Poorly consolidated, brown, red, yellow, grey, siliceous sand, silty clay, clay pellet aggregates; gypsiferous clay pellets, pale grey gypsitic silts; components increasingly modified by pedogenesis; includes intercalated red calcareous and gypsiferous palaeosols with calcrete glaebules; rhizoliths locally capped by white, mobile, well-sorted quartz sand	aeolian dune environment adjacent to deflated lake floors and channs	forms single and multiple lunettes (crescentic, transverse dunes), concave to west, bordering the eastern side of lakes basins; locally flanked by lobeoid dunes of mobile white sand
		Qdp Unconsolidated, red, brown, cream, siliceous sand, clay pellet aggregates, admixed with loamy soils; sand component consists of medium to fine quartz grains with red clay cutans; modified by pedogenesis; includes iron and carbonate cemented nodular grading to calcrete hardpans	aeolian sand sheet and associated lacustrine and claypan environments	forms extensive, flat to gently undulating plains, locally with parallel dunes; fluvio-lacustrine depressions; includes narrow aeolian-modified sand plains adjacent to rivers and lakes
		Qdw Woorinen Formation: unconsolidated, red-brown, siliceous, silty sand, red calcareous silty clay, sandy clay; clay pellet aggregates; gypsiferous clay pellets, pale grey gypsite silts; consists of medium to fine quartz grains with red clay cutans; modified by pedogenesis; includes intercalated red calcareous palaeosols with gypsiferous and salt in resistant calcareous glaebules grading to cemented calcrete hardpans which locally form massive brecciated sheets	aeolian dune and sands	forms extensive dunefields of discontinuous, east–west oriented dunes with subdued crests and flanks; dunes separated by broad swales and sand plains
	EARLY TO LATE PLEISTOCENE	**Qpd** Parthaway Formation: unconsolidated sand, silt, sandy variegated clay, peat; calcareous clay; limpet, freshwater limestone	beach/ridge-lagoonal, swamp, minor lacustrine and locally anchialine; with minor limestone in eastern side of lake basins; locally flanked by lobeoid dunes of mobile white sand	forms widespread, low-lying coastal plains and anchialine; with minor limestone
		Qpb Bridgewater Formation: poorly consolidated, pale yellow, pinkish-brown, fine to coarse, fossiliferous, calcareous, sand; calcarenite; locally capped by calcrete	coastal beach and associated aeolian dune	forms stranded series of elongate beach ridges; subparallel to present coastline
		Qpc Well-cemented, pale grey, fine-grained, dolomitic algal laminites; with intraclasts of sandstone, calcarenite, dolomitic; in places capped by sheet calcrete	marginal-marine, lacustrine-lagoonal	forms flat coastal plain
	EARLY PLEISTOCENE TO HOLOCENE	**Qca** Bakara Calcrete, Ripon Calcrete and other calcrete deposits: strongly cemented, pale grey, massive sheet calcrete, calcrete rubble, friable white, cream, rhizolithic and nodular calcrete; includes intraclasts of various lithologies and in calcrete matrix	pedogenic, groundwater, lacustrine and biogenic	locally forms massive, resistant sheets
		Qrk Pooraka Formation: red, ochre colluvial and residual deposits: unconsolidated, red-brown, poorly sorted clayey sand, gravel, conglomerate, breccia; local calcrete intercalations and capping; in places cemented by ferruginised dolomitic matrix	colluvial sheet wash, alluvial fan and residual log environments	forms extensive, sandsmeet, low-angle fans; high-angle talus cones and scree slopes
	EARLY PLEISTOCENE	**Qpf** Coomandook Formation: partly lithified, grey, cream, fossiliferous, medium-grained quartz sand, calcareous sand, calcarenite, sandy clay; characteristically contains lithic clasts and dolomite/dolcrete derived from older limestone	shallow-marine	entirely concealed
	LATE PLIOCENE TO PLEISTOCENE	**Qpc** Blanchetown Clay, Bungunnia Limestone: poorly consolidated to friable, well-laminated, greenish-grey, red-brown clay; locally marbled, silty, sandy; calcareous and gypsiferous; includes minor intercalated quartz sand, ostracod sand, calcareous, gypsiferous, siliceous nodules; overlies in west by well-cemented Bridgewater Formation consisting of bioclastic marine, eolianite, and/or pisolitic calcarenite; and/or algal stromatolite	predominantly freshwater lacustrine; locally, saline lacustrine and fluvial environments	mainly mantled; locally exposed in river cliffs and gully margins
	LATE TERTIARY TO QUATERNARY	**TDs** Shepparton Formation: unconsolidated to poorly consolidated, mottled, variegated clay, silty clay with lenses of polymictic, coarse to fine sand and gravel; partly modified by pedogenesis; includes intercalated red-brown palaeosols	fluvio-lacustrine, floodplain, channel and levee environments; minor aeolian	forms extensive, flat; alluvial floodplains traversed by remnant traces of inactive, meandering paleochannels
		TDv 'Newer Volcanics': basaltic lava, agglomerate, scoria, tuff and related volcaniclastic sediments	widespread, sub-aerial volcanic	extensive lava and pyroclastic fields in western Victoria contain numerous, small remnant cones, plugs, maars; elsewhere scattered scoriaceous cones, basaltic plugs and flows occur in highland valleys and form stranded plateaux
		TDd Outcrops of red, massive to pisolitic ferruginous subsoil, underlain by mottled clay over pallid zone of white, kaolinitic clay	composite bioclastic duricrust developed over siliceous surfaces in environments subject to deep chemical weathering	forms residual, flat to gently undulating surfaces; Glenelg Tableland; locally deeply dissected to form steep-sided remnants
	PLIOCENE	**Tpn** Norwest Bend Formation: partly cemented, pale grey, brown, yellow, coquinoid limestone with fossiliferous quartz sand matrix; characterised by oyster beds	estuarine	exposed in cliffs of River Murray gorge, elsewhere concealed
	LATE MIOCENE TO PLIOCENE	**Tpa** Loxton–Parilla Sands: unconsolidated to weakly cemented, yellow-brown, fine to coarse, well-sorted quartz sand, with minor gravel, clay lenses; in places cemented by pedogenic carbonate to form sandy limestone; minor shelly, micaceous, quartz sand and gravel facies distributed more locally near or above shoreline; towards the southeast blue-tinted silica, kaolinitic or gibbsitic clay matrix; locally capped by sandy, pisolitic, ferruginous duricrust	composite sand sheet deposited in strand plain and shoreface environments; including shallow-marine, beach and estuarine, flanked and locally overlain by fluvial	forms extensive, undulating, low-angle dune, high-angle talus cones and scree slopes
		Tpv Calivil Formation: poorly consolidated, pale grey, poorly sorted, coarse to granule quartz sand, conglomerate with white kaolinitic matrix; includes thick intercalations of tuvids, thick lenses of carbonaceous clay; grain size diminishes landward where formation includes dark brown, ferruginised grey pyritic peat with minor interbedded arkosic sand and clay	sand sheet deposited in valley fill, alluvial fan, fluvio-lacustrine and braided channel environments	mainly concealed
		Tpb Bookpurnong beds: poorly consolidated to plastic, brown, greenish-grey, calcareous clay (marl), silt, sand; highly fossiliferous, glauconitic, micaceous and locally carbonaceous; characterised by molluscan macrofossils	shallow-marine shelf	mainly concealed
	LATE OLIGOCENE TO MIDDLE MIOCENE	**Tmw** Wonnambool Formation: poorly consolidated, friable to plastic, grey, blue-grey, pale green, glauconitic, highly fossiliferous calcareous clay (marl), with intercalated bioclastic calcarenite, calcareous ooze and dense calcitic limestone; carcareous abundant, well-preserved and diverse faunas	restricted marine platform and lagoonal	entirely concealed
		Tmt Gambier Limestone, Mepunga Formation, Morgan Limestone, Pata Limestone (SA), Duddo Limestone (Vic and NSW): consolidated, well-bedded, pale grey, yellow, white, cream, coarse to medium, highly fossiliferous, bioclastic limestone; with intercalated calcarenite, calcareous ooze and dense calcitic limestone; carcareous abundant, well-preserved and diverse faunas; includes minor intercalations of poorly consolidated calcareous clay (marl); characterised by molluscan macrofossils; Foraminifera; Bryozoa; skeletal debris of diverse, distinctive fossil assemblages	shallow-marine platform	forms cliffs of River Murray gorge; minor karstified outcrops in south-west; mainly concealed
	LATE OLIGOCENE TO EARLY MIOCENE	**Tmg** Geera Clay: poorly consolidated, plastic to friable, black, grey, dark green, silty clay, minor sand; commonly glauconitic, fossiliferous, calcareous, carbonaceous; locally includes sandy dolomitic intercalations; contains abundant low diversity fauna	shallow- and marginal-marine, interdistributary bay, lagoonal and tidal flat	entirely concealed
		Tmk Ettrick Formation: weakly lithified, grey, green, glauconitic, highly fossiliferous, calcareous clay (marl), silt, sandy skeletal clay, with increasing intercalations of skeletal calcarenite towards top; lithologically more variable towards base where includes minor fossiliferous quartz sand; carbonaceous clay; contains abundant and diverse fauna	shallow-marine, restricted platform to lagoonal	entirely concealed
	OLIGOCENE	**Tmc** Compton Conglomerate: lithologically variable, includes partly cemented, medium to coarse, limestone and quartz pebble conglomerate with ferruginised matrix; dark brown loamy clay; grey glauconitic clay; red clay with pebble clasts; yellow, brown, grey, poorly fossiliferous, calcareous limestone and clay (marl)	composite and deposited in sub-aerial/residual and associated transgressive shallow-marine environments	patchy sub-surface distribution in southwest; entirely concealed
	LATE EOCENE TO EARLY OLIGOCENE	**Tnd** Nullarbor beds: poorly consolidated, grey-brown, carbonaceous clay with limonite upper surface; underlain by friable, carbonaceous, grey marl; this limestone forms cave-bearing Nullarbor Plain; overlain by friable, white, bryozoidal limestone with green-grey, glauconitic, calcareous clay (marl)	shallow-marine	entirely concealed
	EOCENE TO MIDDLE MIOCENE	**Tne** Ettrey Formation: unconsolidated to poorly consolidated, thinly bedded, dark brown, grey, black, carbonaceous silt, sand, clay; brown coal, peat; commonly micaceous, pyritic, ferruginised; includes intercalations of poorly sorted, fine to medium quartz sand; palynomic sand; sandy dolomite	fluvio-lacustrine, meandering channel, floodplain and swamp; towards top, in west, includes deltaic, paralic and minor shallow marine	entirely concealed
		Tne Undivided		
	PALEOCENE TO EARLY? EOCENE	**Tw** Warina Sand: unconsolidated, loose to friable, grey, brown, poorly to well-sorted, medium to coarse, quartz sand with minor intercalated fine sand, silt, clay; carbonaceous clay	fluvial	entirely concealed
	PALEOCENE TO MIOCENE	**Tv** 'Older Volcanics': basaltic lava, agglomerate, tuff, small basalt plugs, dykes; associated volcaniclastic sediments	sub-aerial volcanic	numerous small but widespread valley flows and hill cap capsings in highland areas
	TERTIARY	**Tk** Unconsolidated to locally ferruginised, silicified, poorly sorted, pebble to boulder conglomerate, grander to fine sand with sandy clay or kaolinitic matrix; minor silt, clay, kaolin intercalations	high-level residual, valley fill, alluvial and colluvial	erosional remnants exposed in highland valleys and stranded interfluves
	CAINOZOIC	Undivided Cainozoic deposits of small sedimentary basins exposed onshore east of Cape St Vincent and on Kangaroo Island		

* Lacunose and diagenite only

Published by the Groundwater Branch, Bureau of Mineral Resources, Geology and Geophysics (BMR), Department of Primary Industries and Energy, as a contribution to the joint Commonwealth–State Murray Basin Hydrogeological Project, a basin-wide study which is being undertaken in collaboration with the Geological Surveys of South Australia, Victoria and New South Wales, and with the New South Wales Department of Water Resources. Issued under the authority of the Minister for Primary Industries and Energy. Base map compiled by BMR from 1:250 000 topographic maps and digital data. Aeromagnetic surveys supplied by the Australian Surveying and Land Information Group, Department of Administrative Services.

The map was compiled mainly from photographic reductions of 1:250 000 scale geological maps published by the Geological Surveys. Several sheet areas in western New South Wales were previously unmapped at 1:250 000 scale and the geology was compiled from 1:100 000 scale maps. Most of the 1:100 000 maps were published in 1990. Aerial photographic mosaics used to revise transient Quaternary drainage were provided by the participating Geological Surveys and by the New South Wales Department of Water Resources. Landsat imagery was used to identify additional tranT-TERT-TRY-TRY-TRY

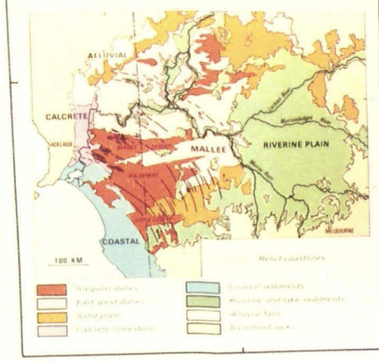
138°
141°
144°
147°
32°
34°
36°
38°

NEW SOUTH WALES
SOUTH AUSTRALIA
VICTORIA

Darling River
Darling Anabranch
Darling River
Murray River
RENMARK
MILDURA
Murray River
ADELAIDE
Lachlan River
Lachlan River
Murrumbidgee River
GRIFFITH
Murrumbidgee River
BALRANALD
Murray River
Murray River
SHEPPARTON
Margin of geological Murray Basin
MT. GAMBIER
MELBOURNE

MURRAY BASIN
LANDSAT MOSAIC
SCALE 1:2 500 000
GEOLOGY OF THE MURRAY BASIN,
SOUTH EASTERN AUSTRALIA —
PLATE 2

0 100 km



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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

ADELAIDE

Lake Alexandrina

Deniliquin

Kingston

Shepparton

Anabranch

Darling

DARLING RIVER

LACHLAN RIVER

MURRUMBIDGEE RIVER

MURRAY

Loddon River

Goulburn River

MORGAN FAULT

HAMLEY FAULT

MURRAYVILLE FAULT

DANYO FAULT

TYRRELL FAULT

LEAGHUR FAULT

CADELL FAULT

MURRAY BASIN

BASE CAINOZOIC STRUCTURE CONTOURS

SCALE 1:2 500 000

0 100 km

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

Computer generated contours based on borehole data available to 1985

Data sources: Brown & Stephenson (1986), including interpretations from Victoria by Lawrence (1975), from S.E. Riverine Plain (Victoria) by Tickell & Humphreys (1979), from Eastern Riverine Plain (N.S.W.) by R.M.Williams (unpublished data, N.S.W. Dep't. of Water Resources), data from Pooncarie 1:250 000 sheet area supplied by J.R.Kellett (BMR).

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA– PLATE 3

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

ADELAIDE

Deniliquin

Kingston

Shepparton

Lake Alexandrina

Lake Tyrrell

Anabranch

Darling

DARLING RIVER

LACHLAN RIVER

MURRUMBIDGEE RIVER

MURRAY

Loddon RIVER

Goulburn River

MORGAN FAULT

HAMLEY FAULT

MURRAYVILLE FAULT

DANYO FAULT

TYRRELL FAULT

LEAGHUR FAULT

CADELL FAULT

50 100 150 200 250 300 350 400 450 500 550 600

138°00' 139°30' 141°00' 142°30' 144°00' 145°30' 147°00'

32°00' 33°00' 34°00' 35°00' 36°00' 37°00' 38°00'

MURRAY BASIN

TOTAL CAINOZOIC ISOPACHS

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

SCALE 1:2 500 000

0 100 km

Computer generated contours based on borehole data available to 1985

Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975), from S.E. Riverine Plain (Victoria) by Tickell & Humphrys (1979) from Eastern Riverine Plain (N.S.W.) by R.M. Williams (unpublished data, N.S.W. Dep't of Water Resources).

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA – PLATE 4

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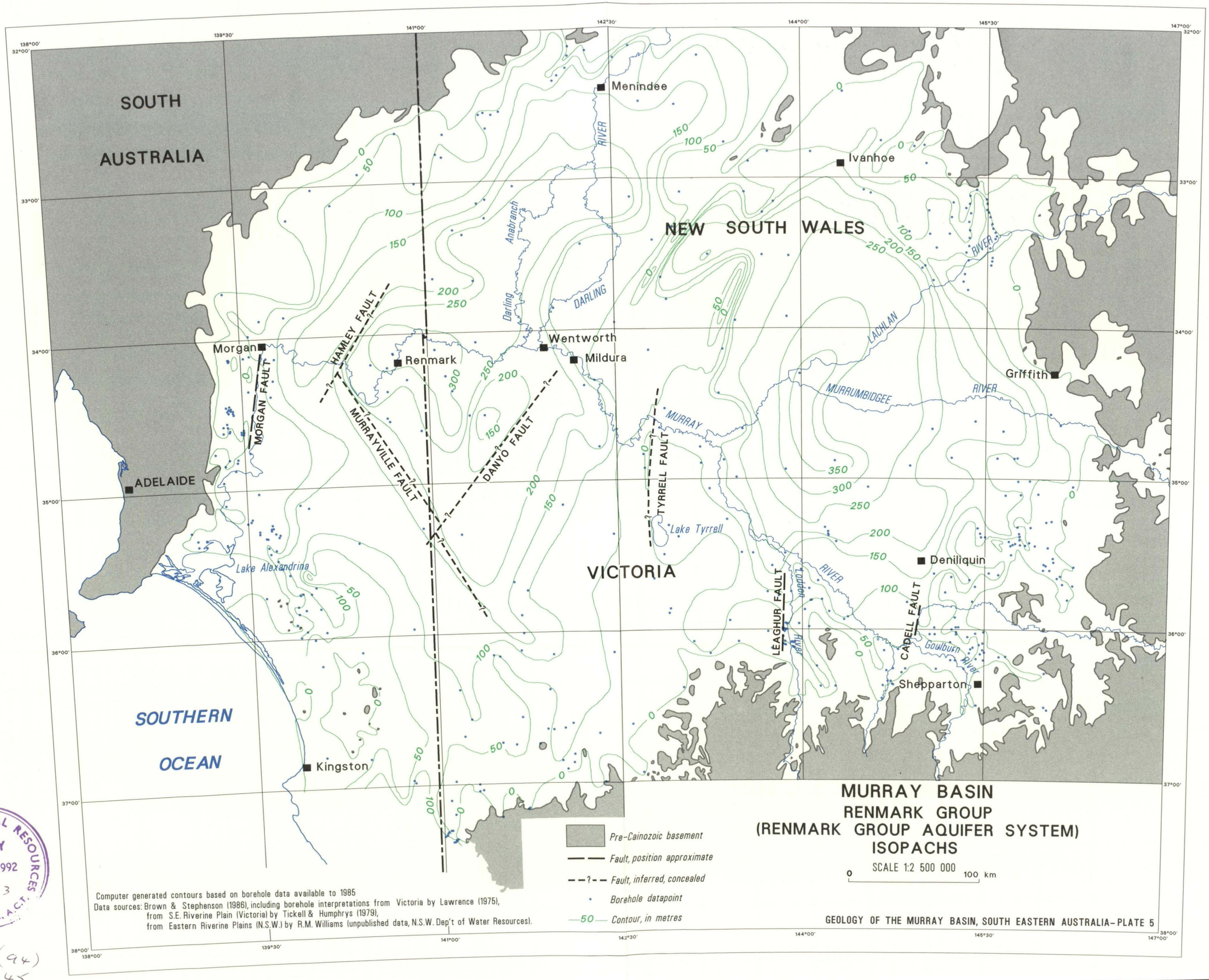

MURRAY BASIN
RENMARK GROUP
(RENMARK GROUP AQUIFER SYSTEM)
ISOPACHS

SCALE 1:2 500 000

Computer generated contours based on borehole data available to 1985
Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975), from S.E. Riverine Plain (Victoria) by Tickell & Humphrys (1979), from Eastern Riverine Plains (N.S.W.) by R.M. Williams (unpublished data, N.S.W. Dep't of Water Resources).

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 5

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

Deniliquin

Shepparton

ADELAIDE

Kingston

Lake Alexandrina

Lake Tyrrell

Anabranch

Darling

DARLING RIVER

LACHLAN RIVER

MURRUMBIDGEE RIVER

MURRAY

Loddon RIVER

Goulburn River

HAMLEY FAULT

MORGAN FAULT

MURRANVILLE FAULT

DANYO FAULT

TYRRELL FAULT

LEAGHUR FAULT

CADELL FAULT

138°00' 139°30' 141°00' 142°30' 144°00' 145°30' 147°00'

32°00' 33°00' 34°00' 35°00' 36°00' 37°00' 38°00'

Computer generated contours based on borehole data available to 1985

Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975), from S.E. Riverine Plain (Victoria) by Tickell & Humphrys (1979), from Eastern Riverine Plain (N.S.W.) by R.M. Williams (unpublished data, N.S.W. Dep't of Water Resources)

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

—50— Contour, in metres

MURRAY BASIN

TOP RENMARK GROUP (RENMARK GROUP AQUIFER SYSTEM) STRUCTURE CONTOURS

SCALE 1:2 500 000

0 100 km

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA– PLATE 6

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

Deniliquin

Shepparton

Kingston

ADELAIDE

Lake Alexandrina

Lake Tyrrell

RIVER

Darling Anabranch

DARLING

LACHLAN RIVER

MURRUMBIDGEE RIVER

MURRAY

Loddon River

Goulburn River

MORGAN FAULT

HAMLEY FAULT

MURRAYVILLE FAULT

DANYO FAULT

TYRRELL FAULT

0 50 100

138°00' 139°30' 141°00' 142°30' 144°00' 145°30' 147°00'

32°00' 33°00' 34°00' 35°00' 36°00' 37°00' 38°00'

MURRAY BASIN

CALCAREOUS CLAY UNITS ETTRICK FORMATION (LOWER CONFINING LAYER) AND WINNAMBOOL FORMATION COMBINED ISOPACHS

SCALE 1:2 500 000

0 100 km

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

Computer generated contours based on borehole data available 1985

Data sources: Brown & Stephenson (1986), Including borehole interpretations from Victoria by Lawrence (1975).

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA– PLATE 7

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

Deniliquin

Shepparton

ADELAIDE

Kingston

Lake Alexandrina

Lake Tyrrell

RIVER

Anabranch

Darling

DARLING

LACHLAN

RIVER

MURRUMBIDGEE

RIVER

MURRAY

Loddon

River

Goulburn

River

MORGAN FAULT

HAMLEY FAULT

MURRAYVILLE FAULT

DANYO FAULT

0

50

100

150

200

250

138°00′ 139°30′ 141°00′ 142°30′ 144°00′ 145°30′ 147°00′

32°00′ 33°00′ 34°00′ 35°00′ 36°00′ 37°00′ 38°00′

MURRAY BASIN

TOP ETTRICK FORMATION (LOWER CONFINING LAYER) STRUCTURE CONTOURS

SCALE 1:2 500 000

0 100 km

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

Computer generated contours based on borehole data available to 1985

Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975).

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 8

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

Deniliquin

Shepparton

ADELAIDE

Kingston

Lake Alexandrina

Lake Tyrrell

RIVER

Darling

Anabranch

DARLING

LACHLAN

MURRUMBIDGEE

MURRAY

TYRRELL FAULT

Loddon

HWAY

Goulburn River

0

50

100

150

138°00′ 139°30′ 141°00′ 142°30′ 144°00′ 145°30′ 147°00′

32°00′ 33°00′ 34°00′ 35°00′ 36°00′ 37°00′ 38°00′

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

Computer generated contours based on borehole data available to 1985
Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975).

MURRAY BASIN

GEERA CLAY
(part of MID-TERTIARY LOW PERMEABILITY BARRIER)
ISOPACHS

SCALE 1:2 500 000

0 100 km

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 9

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

Deniliquin

Shepparton

Kingston

ADELAIDE

Lake Alexandrina

Lake Tyrrell

RIVER

Anabranch

Darling

DARLING

LACHLAN RIVER

MURRUMBIDGEE RIVER

MURRAY

Loddon River

Goulburn River

MORGAN FAULT

HAMLEY FAULT

MURRAYVILLE FAULT

DANYO FAULT

TYRRELL FAULT

138°00' 139°30' 141°00' 142°30' 144°00' 145°30' 147°00'

32°00' 33°00' 34°00' 35°00' 36°00' 37°00' 38°00'

MURRAY BASIN

ETTRICK FORMATION, WINNAMBOOL FORMATION & GERRA CLAY (LOWER CONFING LAYER & MID-TERTIARY LOW PERMEABILITY BARRIER) COMBINED ISOPACHS

SCALE 1:2 500 000

0 100 km

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

Computer generated contours based on borehole data available to 1985

Data Sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975)

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 10

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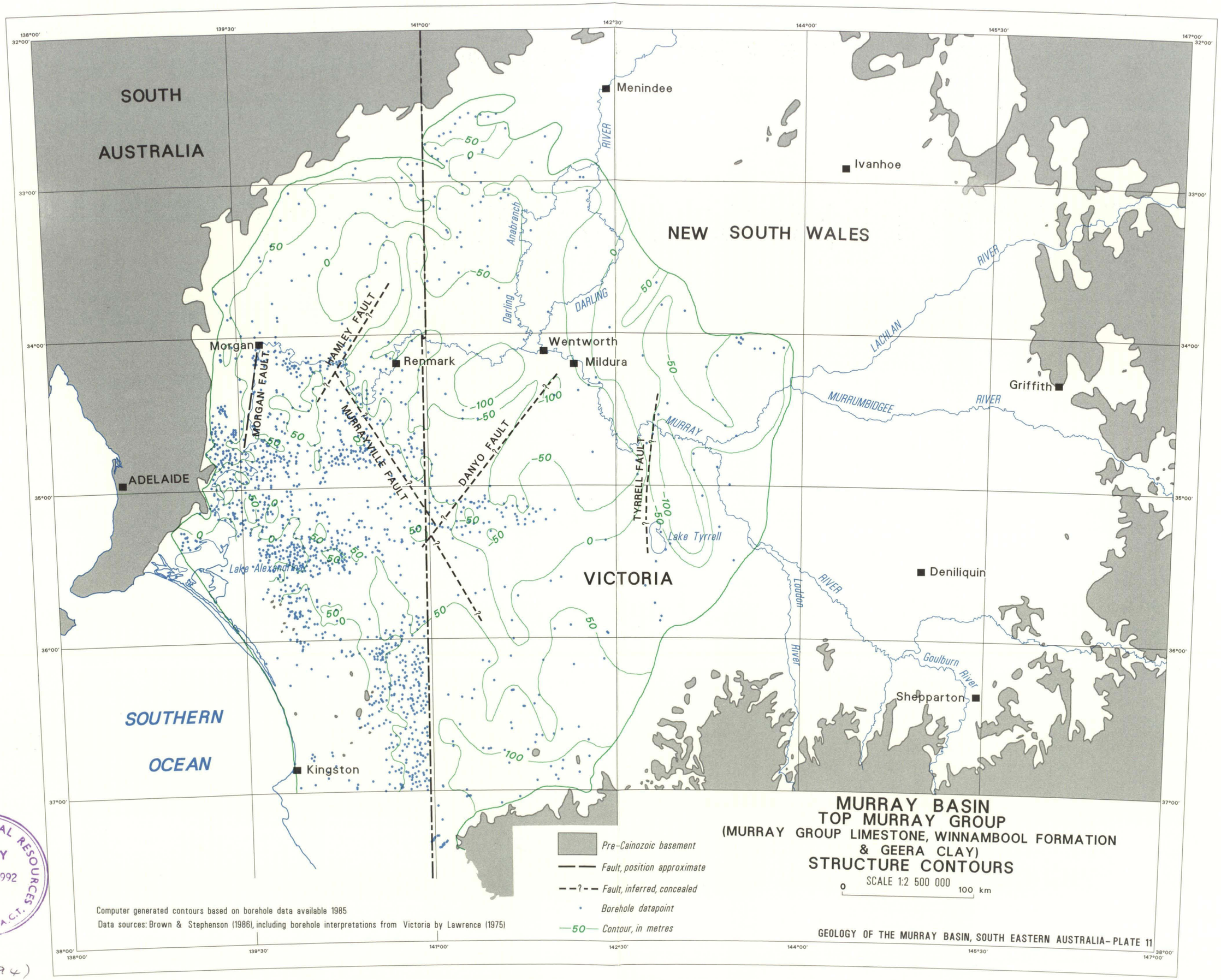

MURRAY BASIN
TOP MURRAY GROUP
(MURRAY GROUP LIMESTONE, WINNAMBOOL FORMATION & GEERA CLAY)
STRUCTURE CONTOURS

SCALE 1:2 500 000

Computer generated contours based on borehole data available 1985
Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975)

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 11

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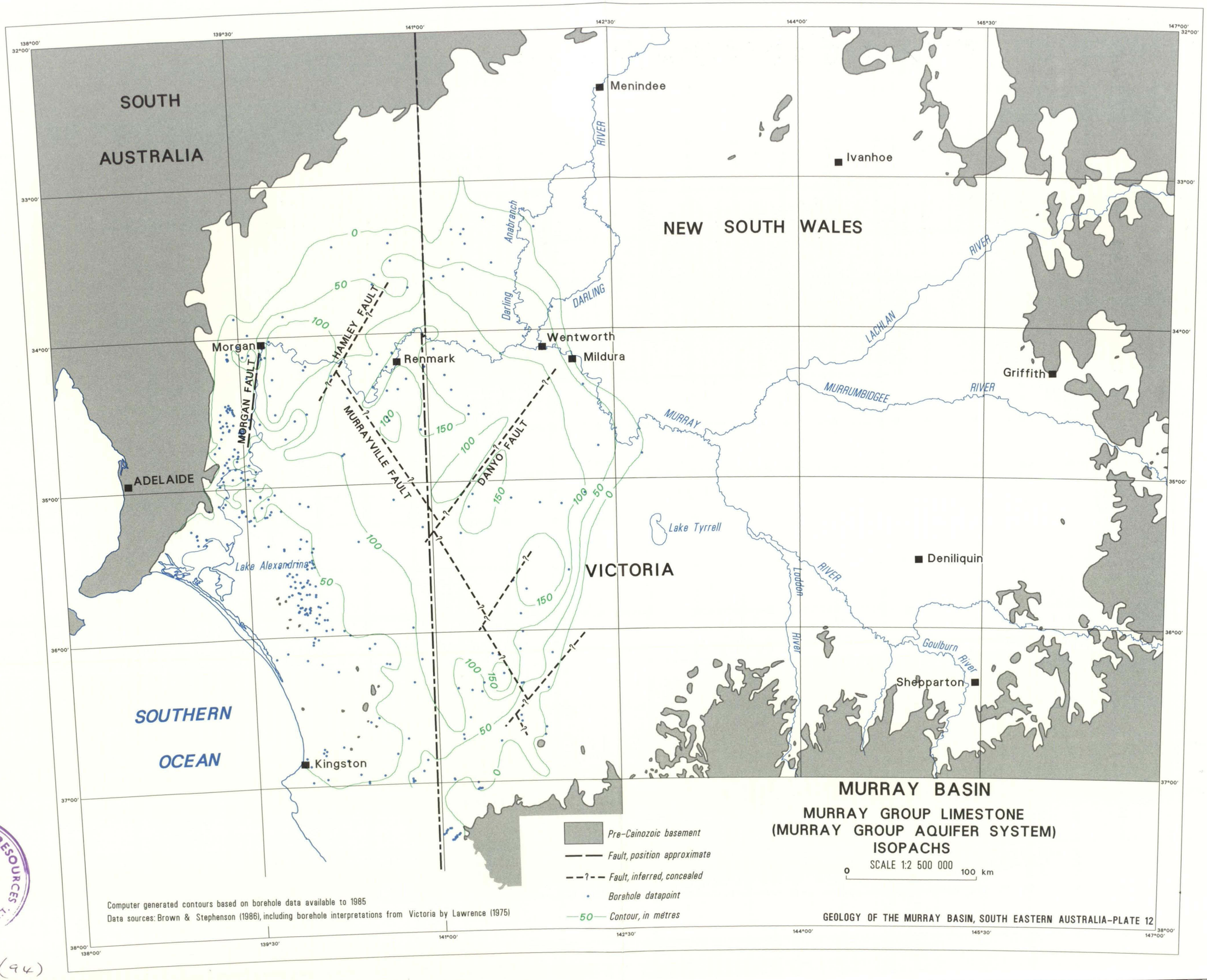

MURRAY BASIN

MURRAY GROUP LIMESTONE
(MURRAY GROUP AQUIFER SYSTEM)
ISOPACHS

Computer generated contours based on borehole data available to 1985
Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975)

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 12

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

ADELAIDE

Deniliquin

Kingston

Shepparton

Lake Alexandrina

Lake Tyrrell

RIVER

Anabranch

Darling

DARLING

LACHLAN

RIVER

MURRUMBIDGEE

RIVER

MURRAY

Loddon

RIVER

Goulburn River

MORGAN FAULT

HAMLEY FAULT

MURRAYVILLE FAULT

DANYO FAULT

-100

-50

0

50

100

150

138°00'
139°30'
141°00'
142°30'
144°00'
145°30'
147°00'
32°00'
33°00'
34°00'
35°00'
36°00'
37°00'
38°00'

Pre-Cainozoic basement

Fault, position approximate

Fault, inferred, concealed

Borehole datapoint

50 Contour, in metres

Computer generated contours based on borehole data available 1985

Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975)

MURRAY BASIN

TOP MURRAY GROUP LIMESTONE (MURRAY GROUP AQUIFER SYSTEM) STRUCTURE CONTOURS

SCALE 1:2 500 000

0 100 km

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 13

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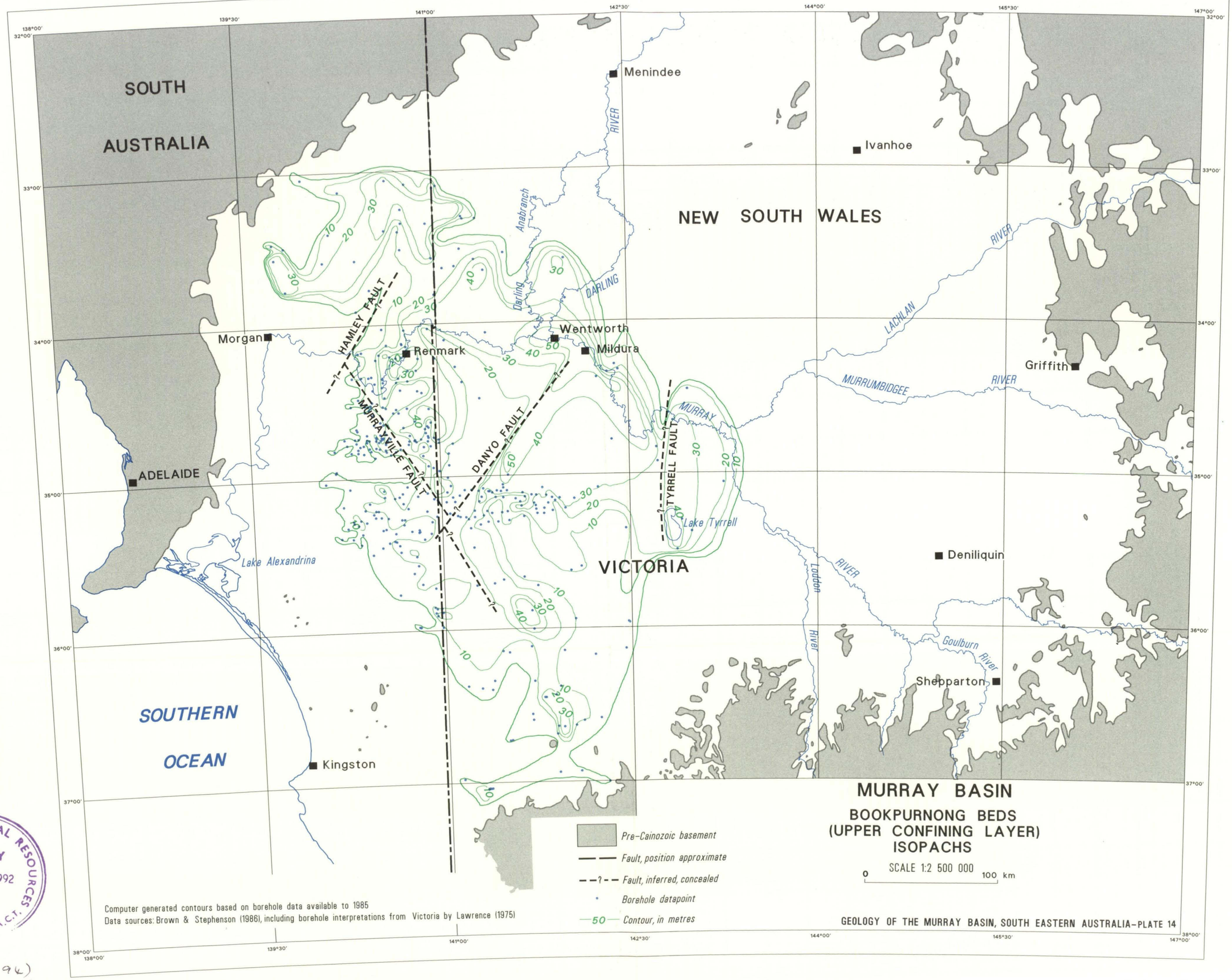

MURRAY BASIN
BOOKPURNONG BEDS
(UPPER CONFINING LAYER)
ISOPACHS

Computer generated contours based on borehole data available to 1985
Data sources: Brown & Stephenson (1986), including borehole interpretations from Victoria by Lawrence (1975)

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 14

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SOUTH AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Menindee

Ivanhoe

Morgan

Renmark

Wentworth

Mildura

Griffith

Deniliquin

Shepparton

Kingston

ADELAIDE

Lake Alexandrina

Lake Tyrrell

Anabranch

Darling

DARLING RIVER

LACHLAN RIVER

MURRUMBIDGEE RIVER

MURRAY

Loddon RIVER

Goulburn River

MURRAY BASIN
BOUGUER GRAVITY ANOMALIES

Pre-Cainozoic basement

—10— Contour, in milligals

SCALE 1:2 500 000

0 100 km

Bouguer gravity anomaly data supplied by A.Murray, Regional Geophysical Mapping, BMR

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA–PLATE 15

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138°
141°
144°
147°
32°
34°
36°
38°

NEW SOUTH WALES
SOUTH AUSTRALIA
VICTORIA

Darling River
Lachlan River
Murray River
Murrumbidgee River
Murray River

MILDURA
GRIFFITH
ADELAIDE
SHEPPARTON
MELBOURNE

Margin of geological Murray Basin

N

0 100 km

MURRAY BASIN
TOTAL MAGNETIC INTENSITY
COLOUR GRADIENT IMAGERY (E–W GRADIENT)
Image processing by V. Anfiloff and S. Dennis,
BMR Geophysical Mapping Program

GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA
PLATE 16

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138°
141°
144°
147°
32°
34°
36°
38°
NEW SOUTH WALES
SOUTH AUSTRALIA
VICTORIA
Darling River
Lachlan River
Murray River
Murrumbidgee River
MILDURA
GRIFFITH
ADELAIDE
SHEPPARTON
MELBOURNE
Margin of geological Murray Basin
N
0
100 km

MURRAY BASIN
TOTAL MAGNETIC INTENSITY
GREY-SCALED IMAGERY (E–W GRADIENT)
Image processing by V. Anfiloff and S. Dennis,
BMR Geophysical Mapping Program
GEOLOGY OF THE MURRAY BASIN, SOUTH EASTERN AUSTRALIA
PLATE 17

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