COMMONWEALTH OF AUSTRALIA
DEPARTMENT OF NATIONAL DEVELOPMENT
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

REPORT No. 134

A Review of the Otway Basin

COMPILED BY

M. A. REYNOLDS

AUSTRALIAN GOVERNMENT PUBLISHING SERVICE
CANBERRA 1971

Best wishes
from Max Reynolds

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A REVIEW OF THE OTWAY BASIN

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INTRODUCTION

Definition of the Otway Basin

The Otway Basin is the western segment of a late Mesozoic (Jurassic or Lower Cretaceous) downwarp, occupying southwestern Victoria and southeastern South Australia and extending offshore. Its onshore limits, shown on Plate 1, have been determined from outcrop and well data; the offshore boundary has not yet been defined but apparently extends beyond the 100-fathom line.

The eastern margin is defined by the Selwyn Fault and its offshore prolongation, indicated by a strong south-southwest aeromagnetic gradient. Precambrian and Palaeozoic basement rocks cropping out east of this lineament, and geophysical evidence, indicate a narrow basement ridge between the Otway Basin and the Gippsland and Bass Basins. The margin continues to the western side of King Island along magnetic lineaments.

From the northwestern side of Mornington Peninsula, the margin turns to the west through Melbourne and probably runs irregularly westwards past Hamilton and to the northwest beneath a cover of Cainozoic volcanics and sediments. From the northwestern edge of Lower Cretaceous outcrop (north-northwest of Casterton), the margin follows the Kanawinka Escarpment, where the escarpment abuts against basement for a short distance, and then swings northwards to Naracoorte. The margin undulates from north of Naracoorte to Kingston along the south side of the Padthaway Ridge and embraces a small area of shallow basement with some Tertiary and possibly older sediments; hydrocarbon occurrences were reported from bores in this area. Geophysical and subsurface data show that a strongly faulted zone exists at depth south of the margin and extends from south of Naracoorte west through Cape Jaffa; Tertiary and Mesozoic sediments thicken south of the fault zone. Tertiary sediments extend from the Otway Basin across the southeastern part of the Padthaway Ridge into the Murray Basin.

Aeromagnetic and marine seismic data indicate that the offshore margin west of Kingston is the sinuous southern edge of a shallow offshore shelf.

Acknowledgments

The assistance given by companies and State Mines Department is gratefully acknowledged; especially that of Frome-Broken Hill Co. Pty Ltd, who made available much unpublished information on the Otway Basin.

Method of study

The Otway Basin review was undertaken by the Subsurface Section of the Petroleum Exploration Branch, Bureau of Mineral Resources, with the assistance of other Branches of BMR, and of the Institut Français du Pétrole (acting as consultants to BMR). The work, which began in October 1963 and was completed by the end of 1966, was directed by M.A. Condon and in his absence by L.W. Williams; and was supervised initially by C.E.B. Conybeare and K.B. Lodwick, and after September 1964, by M.A. Reynolds.

This Report is a condensation of the unpublished review of the Otway Basin (BMR, 1966), covering petrology, literature, geophysics, and reservoir engineering.

Petrological studies. Ten subsidized* wells were chosen for detailed petrological studies (Dellenbach, 1964, 1965a, 1965b; Dellenbach & Hawkins, 1964; Dellenbach, Kraitsowits, Ozimic & Hawkins, 1965; Edworthy, 1964, 1965a, 1965b; Hawkins, 1965; and

* 'Subsidized' refers to operations conducted under the Commonwealth Government's Petroleum Search Subsidy Acts, and indicates that material data from such operations have been available for the review.

Hawkins & Dellenbach, 1963). The studies yielded new information on the sediments, and led to the recognition of a number of lithological units and of at least three unconformities of basin-wide extent. Most of the units have now been formally named (Reynolds, Evans, Bryan, & Hawkins, 1966). The informal letter symbols used by BMR (1966), however, have received wide circulation, and are retained alongside the nomenclature (see Table 2 and Chart 1).

Literature review. More than 500 papers have been written on the Otway Basin. They could not all be examined, but most are listed in a partly annotated bibliography (BMR, 1966). A selected bibliography of the more important papers is given with this report.

Geophysics. Gravity data have been taken directly from BMR Geophysical Branch compilations and from work done for Frome-Broken Hill Co. Pty Ltd by K.A. Richards (1956). The results of aeromagnetic surveys have been collated, but no attempt has been made to reinterpret the records. Most effort has been directed to combining all available seismic data into cross-sections and contour maps of the unconformable horizons recognised in the petrological studies.

Reservoir engineering. Pressure and fluid data have been collated (Scorer, 1965), but are insufficient for construction of pressure flow nets and hydrodynamic analysis.

History of oil exploration

The first well drilled for oil in Australia was the Alfred Flat Bore, drilled in 1892 in the Coorong area (near the Padthaway Ridge in South Australia, part of the northern margin of the Otway Basin). The first deep holes within the basin were water bores, drilled by the Victorian Department of Mines. The Robe No. 1 Bore was drilled to 4505 feet in 1915 by the South Australian Oil Wells Company who subsequently drilled wells at Tantanoola, in the Hundred of Caroline, and near Anglesea. These, and some of the subsequent wildcat wells, were based on surface indications of structure. Mount McIntyre No. 1 was drilled to ascertain whether any oil had accumulated through distillation of organic matter in carbonaceous beds by volcanic intrusion or by the folding of the beds as a result of the intrusion. Only the wells drilled to more than 2000 feet are included in Table 1A; a more comprehensive tabulation is in BMR (1966, Table 1A).

The first application of geophysics to oil prospecting in the Otway Basin (to ascertain the nature of a structure which was about to be drilled for oil) was in 1930, when J.M. Rayner conducted a magnetometer survey on Knights Dome in southeastern South Australia. The subsequent drilling of the dome was, unfortunately, stopped before the whole of the Tertiary section had been penetrated, and results were inconclusive. The next known geophysical work was not undertaken until 1948-49, when the Zinc Corporation flew some aeromagnetic lines in southeastern South Australia and western Victoria. BMR then did some gravity and magnetometer surveying in 1949-50 in southwestern Victoria (Wiebenga, 1957, 1960), and the South Australian Department of Mines ran gravity surveys in southeastern South Australia from 1950 to 1954 (Grant, 1954; and some unpublished work); the results were co-ordinated by Richards (1956). Subsequent surveys, mainly geophysical, are summarized in Table 1B.

TABLE 1A: WELLS AND BORES DEEPER THAN 2000 FEET IN THE OTWAY BASIN

Year	Operator	Name	Location	Elevation G.L. (ft)	Total Depth* (ft)
1894	Victorian Dept. of Mines (V.D.M.)	Portland No. 1	Portland Botanical Gardens		2265
1915	S.A. Oil Wells Co.	Robe No. 1	Sect. 714, Hd. Waterhouse	127.5	4504
1923	Associated Oil Corporation	Mt Gambier No. 1	8 ml NW of Mt Gambier	135	2110
1925	Southern Ocean Oil Co.	Coorong No. 2	Sect. 507, Hd. Lacepede	20	2660
1930	Oil Search Ltd	Knights Dome No. 2	Sect. 170, Hd. Blanche	170	2013
1939 -42	Producing Oilfields Ltd and Western Petroleum N.L.	Portland North	North Portland	17	2835
1941 -45	Bureau of Mineral Resources and V.D.M.	Nelson Bore (or Glenelg No. 1)	Nelson	10	7305
1957 -58	V.D.M.	Portland No. 2	Portland	110	4719
1958 -59	V.D.M.	Portland No. 3	West Portland	16	5638
1959	V.D.M.	Belfast No. 4	Port Fairy	20	5521
1959	V.D.M.	Timboon No. 5	$\frac{1}{2}$ ml S of Timboon	315	3500
1959	Frome-Broken Hill Company Pty Ltd	Pt Campbell No. 1	$3\frac{1}{2}$ ml NW of Pt Campbell	337	5965
1960	Frome-Broken Hill Company Pty Ltd	Pt Campbell No. 2	$1\frac{1}{2}$ ml NW of Pt Campbell	266	8846
1961	Frome-Broken Hill Company Pty Ltd	Pt Campbell No. 3	6 ml NW of Pt Campbell	195	5530
1961	Alliance Oil Development Australia N.L. (Formerly Oil Development N.L.)	Penola No. 1	Sect. 100, Hd. Penola	204	4985
1961	Frome-Broken Hill Company Pty Ltd	Flaxmans No. 1	20 ml SE of Warrnambool	206	11528
1962	South-East Oil Synd.	Beachport No. 1	Sect. 20, Hd. Lake George	13	3963
1962	Alliance Oil Development Australia N.L.	Mount Salt No. 1	12 ml SW of Mt Gambier	70	10044

* Depths measured from datum level.

Year	Operator	Name	Location	Elevation G.L. (ft)	Total Depth* (ft)
1962	Frome-Broken Hill Company Pty Ltd	Pretty Hill No. 1	13 ml NNW of Pt Fairy	189	8124
1962	Alliance Oil Development Australia N.L.	Anglesea No. 1	Anglesea	65	10065
1963	Frome-Broken Hill Company Pty Ltd	Eumeralla No. 1	8 ml E of Tyrendarra	154	10308
1963	Beach Petroleum N.L.	Geltwood Beach No. 1	$7\frac{1}{2}$ ml SW of Millicent	15	12300
1963	V.D.M.	Latrobe No. 1 Bore	Princetown	102(RT)	2054
1963	Frome-Broken Hill Company Pty Ltd	Sherbrook No. 1	5 ml NW of Princetown	467	5434
1963 -64	Frome-Broken Hill Company Pty Ltd	Fergusons Hill No. 1	5 ml N of Princetown	651	11622
1964	Planet Exploration Company Pty Ltd	Heathfield No. 1	10 ml WSW of Casterton	230	7500
1964	Frome-Broken Hill Company Pty Ltd	Port Campbell No. 4	6 ml NNW of Pt. Campbell	427	8520
1964	Planet Exploration Company Pty Ltd		17 ml WNW of Casterton	258	5363
1965	Planet Exploration Company Pty Ltd	Casterton No. 1	4 ml SW of Casterton	461	8183
1965	Alliance Oil Development Australia N.L.	Kalangadoo No. 1	3/4 ml SW of Kalangadoo	228	9040

* Depths measured from datum level

TABLE 1B: OTHER OPERATIONS ASSOCIATED WITH OIL SEARCH

Year	Operation	Operator
1955	Gambier-Otway Aeromagnetic Survey, South Australia	South Australian Department of Mines (SADM)
1956	Western Victoria Gravity Heywood, Western Victoria, Experimental Seismic	Bureau of Mineral Resources (BMR)
1957	Dartmoor-Heywood Gravity	Frome-Broken Hill Company Pty Ltd
	Mt Salt-Mt Schank, Summer Hill, Tantanoola Gravity	Frome-Broken Hill Company Pty Ltd
1957 -58	Port Phillip Bay Gravity	Bureau of Mineral Resources (BMR)
1958	Adelaide-Cape Nelson Aeromagnetic (long line)	Bureau of Mineral Resources (BMR)
1959	Princetown-Warrnambool Seismic, Portland and Port Campbell-Timboon Seismic	Frome-Broken Hill Company Pty Ltd
1960	Port Campbell-Peterborough Seismic	Frome-Broken Hill Company Pty Ltd
1960 -61	Bass Strait-Encounter Bay Aeromagnetic	Haematite Explorations Pty Ltd
	Portland-Otway Area Seismic	Frome-Broken Hill Company Pty Ltd
1961	Gambier Sunklands Seismic	General Exploration Company of Australia Ltd
	Warrnambool-Port Campbell Marine Seismic	Frome-Broken Hill Company Pty Ltd
	Princetown-Warrnambool Seismic	Frome-Broken Hill Company Pty Ltd
1961 -62	Area 3, Southwest Victoria Seismic	Frome-Broken Hill Company Pty Ltd
	Dartmoor-Nelson Seismic	Frome-Broken Hill Company Pty Ltd
	Mayurra, or O.E.L. 22 Millicent-Beachport Seismic	Beach Petroleum N.L.
1962	Mount Salt Structure Drilling	Oil Development N.L.
	Geelong-Adelaide Aeromagnetic (long line)	Bureau of Mineral Resources (BMR)
	Geelong-Adelaide-Leigh Creek Aeromagnetic	Bureau of Mineral Resources (BMR)
	Casterton Seismic	Planet Exploration Company Pty Ltd

Year	Operation	Operator
1962 -63	Southwest Victoria Regional Gravity	Frome-Broken Hill Company Pty Ltd
	Murray Basin Aeromagnetic	Planet Exploration Company Pty Ltd
1963	Gippsland, Bass Strait-Anglesea and S.A. Marine Seismic	Haematite Explorations Pty Ltd
	Geltwood Beach Structure Drilling	Beach Petroleum N.L.
1963	Princetown Seismic	Frome-Broken Hill Company Pty Ltd
	Permit 22 Southwest Victoria Marine Seismic	Frome-Broken Hill Company Pty Ltd
	Branxholme-Koroit Seismic	Frome-Broken Hill Company Pty Ltd
	Murrayville-Casterton Seismic	Planet Exploration Company Pty Ltd
1963 -64	Cooriemungle Seismic	Frome-Broken Hill Company Pty Ltd
1964	Curdie Vale Seismic	Frome-Broken Hill Company Pty Ltd
	Timboon Seismic	Frome-Broken Hill Company Pty Ltd
	Penola Seismic	Alliance Oil Development Australia N.L. (AODA)
	Otway Basin Experimental Vibroseis	Bureau of Mineral Resources (BMR)
	Kalangadoo Gravity	Alliance Oil Development Australia (AODA)
	Branxholme-Koroit Seismic (second)	Frome-Broken Hill Company Pty Ltd
	Koroit Seismic	Frome-Broken Hill Company Pty Ltd
1964	Casterton Supplementary Seismic	Planet Exploration Company Pty Ltd
	O.E.L. 22 Seismic (refraction & reflection)	SADM
1964 -65	Merino Seismic	Alliance Oil Development Australia (AODA)
	Cape Grim to Cape Jaffa Marine Seismic	Haematite Explorations Pty Ltd
1965	Kalangadoo-Lucindale Seismic	Alliance Oil Development Australia (AODA)

STRATIGRAPHY

by P.J. Hawkins and J. Dellenbach

Lithological units were defined on the basis of petrographic studies; existing stratigraphic names were applicable to some units. As the petrographic studies progressed, the units were modified and the descriptions which follow supersede those given in earlier reports. The lithological subdivision of the Otway Basin succession conforms closely to the palynological subdivision (Evans, 1966b), and the subdivision of Leslie (1966). Mesozoic and Cainozoic sediments shown in Table 2 constitute the main Otway Basin succession.

PRE-MESOZOIC

To the north of the Otway Basin is a variety of rocks ranging in age from Precambrian to Upper Palaeozoic which could be expected to continue as basement beneath the Basin.

In South Australia, the metamorphosed sedimentary rocks of the Lower Cambrian (marble, dark phosphatic phyllite) and the Cambrian Kanmantoo Group (a thick monotonous alternation of greywacke, phyllite, and impure quartzite) could be expected to extend subsurface from the eastern side of the Mount Lofty Ranges to the Padthaway Ridge. Farther east, in Victoria, Cambrian black shale with chert is associated with diabase extrusions and crops out mainly along the Mount Stavely and Heathcote thrust-belts (Thomas, 1959) and, less commonly, west of the Grampians and west of Geelong along the Bellarine faulted zone. However, the commonest outcrop north of the Otway Basin in western Victoria is of thick Ordovician mudstone, greywacke, and sandstone, metamorphosed locally to schist and gneiss. Silurian rocks apparently could be expected only east of the Heathcote belt (see Pl. 2).

The Cambrian and Ordovician rocks were metamorphosed by an early Palaeozoic orogeny during which acid plutonic rocks were emplaced.

A thick succession of Upper Devonian to Lower Carboniferous rocks forms prominent outcrops in the Grampians region. At the base is an indeterminate thickness of porphyritic and well banded rhyolite, rhyodacite, agglomerate and tuff (Spencer-Jones, 1965). These are overlain by sediments of the Grampians Group - about 20,000 feet of predominantly quartzose sandstone with siltstone and some mudstone; the sediments are mainly of freshwater origin, although minor marine sedimentary rocks occur in the middle of the sequence. Further acid plutonic intrusions occurred in this region and elsewhere in western Victoria during the Lower Carboniferous Kanimblan Orogeny.

The only other occurrences of Upper Devonian rocks are the volcanics at Mount Macedon and northeast of Melbourne, and the 1000 feet of conglomerate and sandstone at Gisborne (near Mount Macedon) which have been invaded by granodiorite (David, 1950).

There is no evidence to show that the Upper Devonian to Lower Carboniferous sedimentary rocks extend below the Otway Basin. Bain (1957) noted that, although some granite and older basement rocks occurred among the ejectamenta found in volcanic vents near Portland, no fragments of the Grampians Group occurred.

Outliers of Permian fluvioglacial sedimentary rocks with minor marine intercalations* and some thin plant-bearing sandy sedimentary rocks thought to be Triassic in age occur in the Bacchus Marsh area northwest of Melbourne, and in the area north of Coleraine

* G.A. Thomas reported the discovery of marine Permian from near Bacchus Marsh at the ANZAAS Meeting in Hobart, 1965.

TABLE 2: LITHOSTRATIGRAPHIC UNITS OF THE OTWAY BASIN

Age / Group	Formation	BMR Unit	Lithology
PLIOCENE - PLEISTOCENE		Ab	Coarse-grained sandy calcarenite, biocalcarenite, sandy limestone.
			unconformity
OLIGOCENE - MIOCENE HEYTESBURY GROUP		Bb	Limestone (polyzoal, partly dolomitic), marly limestone, spicular marl, with chert in parts.
		Bc	Glauconitic marly limestone (sandy in part).
			unconformity
		C	Brown glauconitic and limonitic marl; limonitic sandstone and conglomerate.
			unconformity
PALAEOCENE - EOCENE WANGERRIP GROUP	Dilwyn Formation	Db	Fine-grained carbonaceous sandstone with subordinate siltstone; coarse argillaceous sandstone to clean fine-grained quartz sandstone, siltstone and shale.
	Pebble Point Formation	Dd	Pebbly sandstone, pelletal and oolitic chamositic sandstone, siderite.
			unconformity
UPPER CRETACEOUS SHERBROOK GROUP	Curdies Formation	Gb	Argillaceous coarse-grained sandstone with coal fragments and stringers.
	Paaratte Formation	Gd	Mainly sandstone and siltstone, chloritic in part; chlorite pellets; carbonate (siderite, dolomite, and calcite) cement in lower part, kaolinite matrix in upper part.
	Belfast Mudstone	Gf	massive glauconitic mudstone.
	Mount Salt Formation	Gg	interbedded and interlaminated sandstone and shelly siltstone (an interfingering of Gf and Gh lithologies).
	Flaxmans Formation	Gh	sandstone and sandy mudstone; chamositic to sideritic oolites, minor phosphate; some volcanic detritus.
			unconformity

Age	Group	Formation	BMR Unit	Lithology
UPPER CRETACEOUS	OTWAY GROUP	Waarre Formation	J-H	Upper orthoquartzite, lower chloritic protoquartzite, with carbonaceous mudstone and coaly horizons; calcite cement in lower part; significant absence of volcanic detritus.
		unconformity		
LOWER CRETACEOUS	OTWAY GROUP	Eumeralla Formation	M	Chloritic mudstone and shale with coaly lenses; subordinate greywacke to subgreywacke and volcanic sandstone; diagenetic calcite, siderite and zeolite, and clay cement.
LOWER CRETACEOUS	OTWAY GROUP	Geltwood Beach Formation 'Pretty Hill sandstone'	P-R	P-lithic garnetiferous sandstone interfingering with fine sediments of Unit M affinities; volcanic and metamorphic detritus; R-lithic garnetiferous sandstone with kaolinite and siderite cement.
		unconformity		
U. JURASSIC – L. CRETACEOUS		Unnamed	T	Conglomerate, lithic sandstone (phyllite fragments mainly) with thin interbeds of mudstone, sideritic in lower part, and shale.
		unconformity		

in western Victoria. Permian rocks are known to occur in the subsurface, and are recorded below the Tertiary in Yalimba Bore near Penshurst (Spencer-Jones, op.cit.). Permian and Triassic spores are widespread at various Tertiary and Cretaceous levels both in outcrop and in wells (Cookson, 1956b; Evans in FBH, 1961; Dettmann in AODA, 1966).

Known basement rocks

Basement rocks have been reached by only four of the wells upon which this study was based: Kalangadoo No. 1, 6755 to 9040 feet; Casterton No. 1, 8022 to 8183 feet; Pretty Hill No. 1, 7874 to 8124 feet; and Fergusons Hill No. 1, 11,513 to 11,622 feet.

In Kalangadoo No. 1, light grey to dark brown siltstone and claystone, regionally metamorphosed and sericitized, occur from 6755 to 9040 feet. Dips are consistently high in these rocks and an angular unconformity separates them from the Geltwood Beach Formation. Gas was recovered from a drillstem test in Kalangadoo No. 1 over the interval 6890-7005 feet. Analysis of the gas indicated that it was composed chiefly of carbon dioxide with only minor hydrocarbons (2-3%).

In Casterton No. 1 basement is a brittle grey biotite-sericite schist with patches of calcite and minor pyrite. In Fergusons Hill No. 1 a schist containing well developed sericite bands and strongly interlocked quartz grains and calcite was observed. The degree of metamorphism in both these wells is much higher than at Kalangadoo No. 1.

In Pretty Hill No. 1, a dark green dense holocrystalline very fine-grained rock, probably lamprophyre, which is much fractured and weathered, is thought to be basement.

The metamorphic rocks and the weathered lamprophyre (which proved unsuitable for isotopic dating) have been tentatively regarded as Cambro-Ordovician, because they are similar to rocks of that age described from outcrop.

MESOZOIC

Mesozoic sediments are divisible into five main rock bodies: Unit T, the Geltwood Beach Formation (with unit R), the Eumeralla Formation, the Waarre Formation, and the Sherbrook Group.

Unit T (unnamed)

Unit T is known only in Casterton No. 1 from 6765 to 8022 feet; the thin lithic sandstone from 11,490 to 11,513 feet in Fergusons Hill No. 1 may also be of this unit. However, a basal conglomerate has been recorded by Kenley (1945) in the Casterton area, and Coulson (1930) described a basal conglomerate in the Barrabool Hills which he regarded as the base of the Otway Group.

Basic criteria for the recognition of Unit T in the Casterton area are:

(i) the presence of conglomeratic beds;

(ii) subangular poorly sorted detritus;

(iii) greater proportion of quartz than of rock fragments and feldspar in subgreywacke beds.

Lithology. The lower part of the unit is predominantly sideritic mudstone and shale; the upper part is poorly sorted lithic sandstone with thin interbeds of mudstone. A conglomerate which occurs within the sequence is composed mainly of metamorphic rock fragments.

Shale with carbonaceous and coaly laminations, interspersed with thin dolerite bands, occurs towards the base of the unit. Contact metamorphism is negligible and the vesicular texture of the dolerite suggests that it formed as flows rather than intrusions.

The lithic sandstone in the upper part of the unit is light grey, compact, subangular, fine to very coarse-grained, poorly sorted although occasionally bimodal, and sericitized.

Porosity is poor (9%) and permeability negligible according to core analyses, but more porous sands between cores are indicated by electric logs.

Three conglomeratic bands have been recognized in Casterton No. 1: a sandy conglomerate at the top of Unit T and two conglomeratic sandstones lower in the sequence in the sandstone and mudstone parts. Their porosity is 14% to 15% and permeability 1 to 2 md. Strong interpenetration of phyllite fragments and interstitial patches of calcite have reduced the porosity in places.

Environment of deposition. The sediments are paralic and alluvial, derived from an area of high relief and deposited in quiet water.

The mudstone and shale, which are laminated and contain siderite, carbonaceous material, and plant remains, were deposited in quiet shallow possibly marine waters. The sandstone, which is confined mainly to the upper part of the unit, indicates rapid deposition because of its angularity, coarseness, and poor sorting. Metamorphosed Ordovician rocks which crop out some 10 miles north and northeast of Casterton No. 1 may be the source of abundant soft phyllite pebbles in parts of Unit T in that well.

Age. Isotopic dating of penecontemporaneous basic intrusions or lava flows within Unit T gives a Jurassic or Cretaceous age. Geochron determined a total rock age by K-Ar dating of 153 ± 5m.y. (in Harding, 1969), an Upper Jurassic age; the A.N.U. determination, however, was only 120 ± 10 m.y., a Lower Cretaceous age. The upper sandstone contains basalt fragments of similar composition to the interspersed igneous bodies, indicating that some lava flows occurred in the Otway Basin at about the time of the sandstone deposition, or that the earlier flows were eroded before burial. Mary White (in Planet, 1965) identified plants which range in age from Jurassic to Lower Cretaceous. Palynological determinations (Evans, 1966b) give a Jurassic age.

Relation to Geltwood Beach Formation. A marked lithological change occurs at the boundary between Unit T and the Geltwood Beach Formation: the sandy conglomerate containing abundant pebbles of phyllite is overlain by basal shale of the Geltwood Beach. No marked change in dip is indicated from the dipmeter survey.

Hydrocarbon occurrences. No oil staining has been observed in the sediments. A drillstem test in Casterton No. 1 over the interval 6995 feet yielded 900 feet of muddy salt water, with a salinity of about 35,000 ppm (as NaCl) calculated from the SP log.

Otway Group

The Geltwood Beach Formation, Unit R ('Pretty Hill sandstone'), Eumeralla Formation, Waarre Formation and Unit H (unnamed) make up a re-defined Otway Group. The distribution of these units is shown in Table 3.

TABLE 3: DISTRIBUTION OF THE OTWAY GROUP UNITS

Western Half of Basin		Eastern Half of Basin	
Mt Gambier area	Pretty Hill area	Port Campbell area	Torquay area
		Waarre Formation (J)	Unit H (unnamed)
Eumeralla Formation (M)	Eumeralla Formation(M)	Eumeralla Formation (M)	Eumeralla Formation (M)
Geltwood Beach Formation (P)	'Pretty Hill sandstone' (R)		

Geltwood Beach Formation (Unit P and Unit R)

A unit was defined between the lamprophyre basement and the Eumeralla Formation (M) in Pretty Hill No. 1 Well (Edworthy, 1964). This is Unit R, the characteristic 'Basal Sandstone' (Bain in FBH, 1962) or 'Pretty Hill sandstone'. In the western part of the Otway Basin sediments of Unit R lithology are interbedded with sediments similar to those of the overlying Eumeralla Formation (M). This mixed succession seems to be a facies variant of the Geltwood Beach Formation (P) - a unit of mixed lithologies first described from both Eumeralla No. 1 (Edworthy, 1965a) and Geltwood Beach No. 1 (Dellenbach, 1965a). A formal name has not yet been given to Unit R because of its limited known occurrence.

The Geltwood Beach Formation, not known in outcrop, was partly penetrated in six subsidized wells and fully penetrated in two other wells in the western part of the Otway Basin. In the eastern part of the Otway Basin the only well - Fergusons Hill No. 1 - to intersect the full sequence of sediments to the Cambro-Ordovician basement did not encounter the formation.

Lithology. Unit R represents a sandstone facies derived from a single source area. The Geltwood Beach Formation includes a sandstone facies containing admixtures of volcanic, granitic, and metamorphic fragments, interdigitating with fine-grained sediments with Eumeralla Formation affinities apparently derived from two source areas.

The Geltwood Beach Formation (P) consists predominantly of chloritic mudstone, with subordinate fine to coarse-grained sandstone mainly subgreywacke in composition; in Casterton No. 1 very coarse-grained sandstone is present. Carbonaceous material is abundant. The characteristic feature of the sandstone is the abundance of pink and brown grains of garnet. The sandstone contains either a chemical cement or a clay matrix. Other basic criteria for the recognition of the sandy fractions of the Geltwood Beach Formation are: admixture of fragments of metamorphic rocks and fresh volcanics; moderately sorted angular to subrounded fine to coarse-grained detritus; preponderance of subgreywacke; truncations, scour-and-fill structures, load casts, micro-faults and slump structures, ripple markings and strong cross-bedding.

In Pretty Hill No. 1, Unit R is similar but lacks fresh volcanic detritus and interbedded mudstone.

Diagenesis is more marked than in Unit T, perhaps because of the more heterogeneous composition of the Geltwood Beach and Eumeralla Formations: the sandstone is cemented and fractures and fissures generally filled.

Pretty Hill No. 1 intersected a lithic sandstone with kaolinite and minor siderite cement (Unit R), from 5964 to 7874 feet (top of basement). The sandstone is light grey, friable, subangular, coarse and moderately sorted. The cement (up to 25%) is kaolinite and siderite with secondary quartz overgrowths. Porosity is up to 25%. Coal fragments are abundant in some layers. Abundant garnet, similar to that in the Geltwood Beach Formation, is the only heavy mineral in the sandstone of Unit R and indicates a source of high-grade metamorphic or possibly granitic rocks.

In Casterton No. 1 the Geltwood Beach Formation becomes more sandy towards the base, and electrical logs indicate that porosity increases in the sandier sequence.

Age. Evans (1966b) places the P-R sequence in the Lower Cretaceous, within the K1 division, and mainly in the K1a zone.

Relation of Geltwood Beach Formation (Unit P) and Unit R to Eumeralla Formation. The Eumeralla Formation appears to be conformable on the Geltwood Beach Formation (P) and Unit R. The change generally occurs over a short interval, and is marked by sudden increase in the amount of garnets.

Environment of deposition. Sediments of the Geltwood Beach Formation are inner paralic to alluvial: high-energy features alternate with quiet shallow-water features. The occurrence of subgreywacke, containing depositional calcite and mudstone with plant fragments and coal lenses, possibly indicates a transitional environment in which marine and non-marine influences alternated. The lithic constituents suggest that the sediments were derived partly from a regionally metamorphosed source area, and partly from an acid to intermediate igneous source area. Unit R was deposited in a similar environment.

The appearance of acritarchs in the Geltwood Beach Formation in core 14, 6296 feet, Casterton No. 1, and that of the unicellular organisms 'Gen. et sp. indet. Forma A' in abundance in core 12, 5609 feet, Casterton No. 1 and core 19, 5590 feet, Heathfield No. 1, imply a near-marine environment.

Salt water was obtained from drillstem tests in the Geltwood Beach Formation in Casterton No. 1 (but at different levels from the microplankton occurrences), and in the Tullich and Pretty Hill wells.

Hydrocarbons. Gassy water in Tullich No. 1 (gases mainly methane and nitrogen) is the only indication of hydrocarbons in Unit P-R.

Eumeralla Formation (Unit M)

Sediments of the Eumeralla Formation from Port Campbell No. 2 well were described by Dellenbach & Hawkins (1964).

Distribution. Lower Cretaceous sediments of the Eumeralla Formation are exposed mainly in the Casterton area and the Otway Ranges. Coulson (1930) has described a section containing Lower Cretaceous sediments in the Barrabool Hills area. Small outcrops also occur along the northern side of the Bellarine Peninsula, and the eastern side of Port Phillip Bay.

The formation occurs in all subsidized wells that penetrated the Lower Cretaceous with the possible exception of Port Campbell No. 1. The literature shows that Lower Cretaceous sediments have been reached in many other wells and bores. The main occurrences are listed in Table 4.

TABLE 4: SUBSURFACE OCCURRENCES OF EUMERALLA FORMATION

Well Name	Datum (ft above sea level)	Depths below Datum Level	Thickness (ft)	Area
Beachport No. 1	18	1920 to 3962	2043+	
Geltwood Beach No. 1	30	3670 to 8955	5285	Mount
Kalangadoo No. 1	230	2560 to 5600	3040	
Penola No. 1	209	1040 to 4400	3360	Gambier
Tullich No. 1	272	418 to 4770	4352	
Heathfield No. 1	244	1680 to 7408	5728	
Casterton No. 1	472	60 to 4850	4790	
Eumeralla No. 1	167	3108 to 9110	6002	Tyren-
Pretty Hill No. 1	202	2929 to 5964	3035	darra
Flaxmans No. 1	221	7430 to 11,528	4098+	
Port Campbell No. 2	282	8514 to 8846	332+	Port
Port Campbell No. 3	210	4810 to 5530	720+	
Port Campbell No. 4	440	5340 to 8520	3180+	Campbell
Sherbrook No. 1	480	4050 to 5434	1384+	
Fergusons Hill No. 1	651	2514 to 11,490	8976	
Latrobe No. 1	102	1970 to 2054	84+	
Anglesea No. 1	78	1921 to 10,065	8144+	Torquay

Lithology. The sequence, up to 9000 feet thick (Fergusons Hill No. 1), is strikingly uniform over the whole basin and consists of chloritic mudstone and shale with subordinate thinly bedded lithic sandstone and coal.

Coal occurs in seams and lenses, 2 to 10 feet thick. Edwards & Baker (1943) state that the coal is bituminous and is generally very finely banded; vitrain forms only a small proportion of these bands, the bulk consisting of dull coal.

Edwards & Baker (1943) noted the predominance of mudstone over sandstone in the sediments of the Otway Ranges Eumeralla Formation, and that mudstone constitutes 75% of the sequence in the northern part of the Otway Ranges and at least 6% in the north-western part of the Otway Basin. These results are confirmed by studies of the sand/shale ratio (BMR, 1966).

Sandstone in lower beds is predominantly greywacke; subgreywacke and lithic (volcanic) sandstone are more common in the upper part. The sand/shale ratio is higher in the upper beds.

Because it contains more subgreywacke and therefore has a higher average porosity, the upper part of the Eumeralla Formation could be regarded as a more prospective target for hydrocarbons than the lower part. Lenses, of quartz sandstone different from typical Eumeralla Formation, have been found in northern and western parts of the

Mount Gambier area. The 'Heathfield Sand'* derived from a metamorphic source has been identified in Geltwood Beach No. 1 (6050-6080 ft), Tullich No. 1 (2974-3094 ft), Heathfield No. 1 (4115-4144 ft), and Casterton No. 1 (1959-2025 ft); and a lower sandstone unit, derived from a mainly granitic source, occurs in Penola No. 1 (3160-3180 ft), and Tullich No. 1 (3769-3814 ft).

Fragments of low-grade metamorphic rocks occur in the 'Heathfield Sand' in variable amounts and distinguish it from the lower sandstone, in which rock fragments are chiefly granitic with minor amounts of metaquartzite. Cement is only patchily developed and the porosity range is 20-25% with very good permeabilities. One characteristic common to both the 'Heathfield Sand' and the lower sandstone unit is the absence of volcanic rock fragments. With these exceptions the abundance of detritus of volcanic origin is the outstanding feature of Eumeralla sediments. The detritus includes a wide range of volcanic rock fragments (Edwards & Baker, 1943; Fander in FBH, 1946b), minerals normally associated with volcanics, and their alteration products, and bentonitic beds (Darragh & Bowen, 1965) (Geltwood Beach No. 1 final report - BPNL, 1964). Volcanic agglomerate containing charred wood fragments has been reported **from** the Gellibrand area of the Otway Ranges (Bell, 1961).

These volcanic materials have been ascribed to the erosion of volcanic terrain from the Upper Palaeozoic basement (Edwards & Baker, 1943), but present evidence suggests contemporaneous Lower Cretaceous volcanic flows as the source. The predominance of flow-textured intermediate volcanic rock debris; the scarcity of crystal and vitric tuffs (of direct pyroclastic origin); and the apparent absence of morphological features such as craters, may confirm this.

Dellenbach (1965b) was able to divide the Eumeralla in Anglesea No. 1 into subunits M1 (upper) and M2. Subunit M1 was marked by an increase in the volcanic detritus present, and Dellenbach suggested that vulcanism recrudesced in M1 time. The M1-M2 boundary in Fergusons Hill No. 1 appeared to coincide with an angular unconformity shown by dipmeter results, but no such break could be proved elsewhere in the Otway Basin; nor could the widespread effect of volcanic recrudescence in M1 time be substantiated. The appearance of abundant volcanic detritus through the Eumeralla Formation probably indicates several episodes of vulcanism, one of which was centred to the east or south-east of the Basin and gave rise to subunit M1 in Anglesea No. 1; penecontemporaneous sedimentation may have masked the effects of that particular episode to the west.

<u>Age of sediments.</u> Evans (1966b) has established that the Eumeralla Formation is mainly Lower Cretaceous but extends up into the Upper Cretaceous <u>Ascodinium parvum</u> zone in Geltwood Beach No. 1.

<u>Relations of Eumeralla Formation to overlying units.</u> The Eumeralla Formation is thought to be unconformable beneath the overlying sediments. In the particular case of the Port Campbell area, the nature of the sediments above the unconformity and their relations to the Eumeralla Formation will be studied in the section dealing with the Waarre Formation (J).

In the western part of the Basin, the top of the Eumeralla is rich in carbonates: the carbonate could represent either a recrystallized product of sedimentation or a late diagenetic introduction in the topmost layers of the formation, below an unconformity. A pellicular chlorite layer is also present near the top of the formation.

<u>Environment of deposition of Eumeralla Formation.</u> Conditions of low energy, interrupted by short periods of high energy, prevailed throughout the Basin during the

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* The 'Heathfield Sand' was first recognized by J.R. Cundill (in PEC, 1964) and was also referred to informally by Brown (1965).

Lower Cretaceous. The homogeneity of the sediments indicates a generally consistent pattern of sedimentation.

The region was one of tectonic instability, with shallow-water sedimentation keeping pace with subsidence. In the Mount Gambier area, marginal marine conditions (Taylor, 1964b) appear to have existed, with broad flood plains traversed by stream channels, marshes, mudflats, and localized deltaic fans; large deposits of peat and coal were not formed. In the easternmost part of the basin sedimentation also took place on broad flat plains. A restricted environment developed within the alluvial flats, swamps, and deltas. Coal developed from drift material probably derived from areas around the eastern end of the basin. Some marine inundation occurred in the Port Campbell area.

Hydrocarbon occurrences. Flows of gas and salt water with gas in solution have been obtained from the Eumeralla Formation: Port Campbell No. 4 produced 36 barrels/day of emulsified crude oil. None of the gas flows was sustained; so the reservoirs were small or restricted.

Porosity and permeability. In parts of the western half of the basin, good permeability and porosity have been found, particularly in sandy beds such as the 'Heathfield Sand'. However, few well developed and permeable sands have been drilled within the Eumeralla Formation in the eastern part. Fracture porosity has yielded small amounts of gas.

Waarre Formation (Unit J and Unit H)

The Waarre Formation (J) lies between the Eumeralla Formation and the Sherbrook Group in the Port Campbell area. Both contacts are unconformable. In Anglesea No. 1, a thin sequence in a similar stratigraphic position and of similar lithology to the Waarre Formation has been called Unit H. The two units are thought to be correlative although there is no palaeontological evidence to support the correlation.

The Waarre Formation was first described by Bain & McQueen (in FBH, 1960a), and the description was amplified by Dellenbach & Hawkins (1964) and Edworthy (1965b). Unit H was described by Dellenbach (1965b).

The Waarre Formation is not known to crop out; it has been intersected by wells and water bores in the eastern part of the Otway Basin, to which it may be confined (see Table 5).

TABLE 5: INTERSECTIONS OF THE WAARRE FORMATION AND UNIT H

Well Name	Datum (ft a.g.l.)	Depths Below Datum Level (ft)	Thickness (ft)	Sand: Shale Ratio	Area
Flaxmans No. 1	221	6880 to 7430	550	1.3:1	Port Campbell
Port Campbell No. 1	346	5650 to 5965	315*	1.4:1	
Port Campbell No. 2	282	8110 to 8514	404	1.8:1	
Port Campbell No. 3	210	4608 to 4810	202	1.8:1	
Port Campbell No. 4	440	4970 to 5340	370		
Sherbrook No. 1	480	3780 to 4050	270	1.1:1	
Fergusons Hill No. 1	651	2046 to 2514	468	1.5:1	
Latrobe No. 1	102	1750 to 1970	220	6:1	
Anglesea No. 1	78	1816 to 1921	105	1.6:1	Torquay

* Waarre Formation not fully penetrated

Lithology. The unit is divided into a lower sequence of chloritic protoquartzite cemented by calcite, with carbonaceous siltstone, mudstone, and coal, and an upper sequence of orthoquartzite and carbonaceous siltstone and mudstone. The sandstones range from fine-grained to conglomeratic and there is a significant absence of volcanic rock fragments. The sand/shale ratio typically ranges between 1.1 and 1.8 (average 1.5) but in Latrobe No. 1 (south of Fergusons Hill No. 1, see Pl.1) the ratio is 6.

Age. The Waarre Formation is mainly in Evans' K2b palynological zone (Lower Cretaceous), extending up into the Ascodinium parvum Zone (Upper Cretaceous) in Flaxmans No. 1 and Port Campbell No. 2.

The upper part of the Eumeralla Formation and basal beds of the Mount Salt Formation in the western part of the basin are of the same age.

Relation of Waarre Formation to Eumeralla Formation. Although parts of the Waarre and Eumeralla Formations are of the same age the two units have different origins, the Waarre being derived from a granitic-metamorphic source (BMR, 1966).

The well intersections lie almost in a straight line, so the distribution and thickness of the body of the Formation cannot be delineated. It appears to thicken towards the central part of the Port Campbell area, and so differs from sandstone bodies in the Eumeralla Formation (Heathfield area), which wedge out towards the central axis of the basin.

Relation of Waarre Formation to overlying units. Both the Waarre and Eumeralla Formations (where Waarre Formation is missing) are covered unconformably by the Sherbrook Group in the western and Port Campbell parts of the basin. These Sherbrook Group beds were deposited during a marine transgression which did not reach the Anglesea area, where Unit H is unconformably overlain by the Eastern View Coal Measures (Curdies Formation correlative).

Environment of deposition. A paralic environment is indicated low in the sequence where probable marine or partly marine mudstone and sandstone are interbedded with coaly layers. Higher in the sequence coarser terrigenous sands followed by a conglomerate indicate a subsequent regression of the sea.

Hydrocarbon occurrences. Port Campbell No. 1 produced a substantial flow of gas which was not sustained. Port Campbell Nos 2 and 3 produced gas and salt water. All other wells in the Port Campbell area produced either salty or fresh water.

Porosity and permeability. The sandstone of the Waarre Formation is mostly very porous and permeable. The range of highest porosities measured on available cores is 20-25%, and the maximum measured permeability is 895 md (Flaxmans No. 1, core 24, 6882-6903 ft). The cuttings, the electric logs, and the failure to recover cores in some intervals, indicate that even more porous and permeable sandstone and conglomerate exist.

Sherbrook Group (Unit G)

The Sherbrook Group (G) was established in the Nelson Bore (Hawkins & Dellenbach, 1963) and Port Campbell No. 1 (Dellenbach & Hawkins, 1964).

It is unconformable between either the Waarre or Eumeralla Formations and the Wangerrip Group. Five subdivisions have been recognized: Curdies Formation (Unit Gb), Paaratte Formation (Unit Gd), Belfast Mudstone (Unit Gf), Mount Salt Formation (Unit Gg), and Flaxmans Formation (Unit Gh).

Outcrops of the Sherbrook Group are unknown, but the Group extends subsurface throughout most of the Basin.

The sandstone and sandy mudstone of Flaxmans Formation at the base of the Group in the Port Campbell area contain chlorite ooliths and pellets; the sandstone has a siderite cement. The Belfast Mudstone is massive glauconitic mudstone with minor sandy beds. In the west, the Mount Salt Formation, a mixture of Belfast and Flaxmans rock types found in the Mount Gambier area, is predominantly silty in the lower part, followed by a more sandy sequence towards the top. The overlying Paaratte Formation contains siderite-cemented sandstone with chlorite pellets, and friable kaolinitic sandstone. This is succeeded by Curdies Formation, a coarse-grained sandstone with detrital clay matrix, and carbonaceous pyritic mudstone and shale.

Flaxmans Formation (Unit Gh)

The Flaxmans Formation (Bain, in FBH, 1961; Bock & Glenie, 1965) has been recognized from wells in the Port Campbell area.

The maximum thickness of the Flaxmans Formation is the 280-foot type section in Flaxmans No. 1 Well. The unit also occurs in Pretty Hill No. 1, Port Campbell Nos 1, 2, and 4, and Sherbrook No. 1.

Lithology. The formation consists of sandstone and sandy mudstone. The sandstone contains quartz, feldspars, and lithic fragments. The sandy mudstone contains ferruginous chlorite ooliths and pellets, with related siderite and minor phosphate, all of which are diagnostic for the Formation.

Age. The age is Upper Cretaceous (*Ascodinium parvum* Zone) (Evans, 1966b).

Relation to overlying units. Flaxmans Formation appears to be more restricted laterally than the overlying Belfast Mudstone and the contact between the two is conformable, partly gradational. Taylor (1964b), however, suggests that in the Port Campbell area, the 'Flaxmans Beds' (with which the formation is correlated) extend northerly, beyond the limit of the Belfast Mudstone, and are overlapped by the marginal Paaratte Formation.

Environment of deposition. Flaxmans Formation was deposited in a transgressive nearshore shallow marine environment with recurrent high-energy conditions. The nearby landmass supplied detritus from metamorphic basement and Lower Cretaceous sediments. Volcanic detritus could either be derived from older deposits, or represent the last manifestation of the vulcanism which began in the Upper Jurassic and continued spasmodically through the Lower Cretaceous; its source appears restricted to the Port Campbell area.

Hydrocarbon occurrences. No evidence of hydrocarbons has been noted; the formation has very low porosity and permeability.

Belfast Mudstone (Unit Gf)

Bain & McQueen (in FBH, 1960a, b) introduced the name Belfast Mudstone to designate a glauconitic mudstone which was intersected in Port Campbell Nos 1 and 2 Wells (BMR Unit Gf).

The Belfast Mudstone has been recognized in Fergusons Hill No. 1 Well and the Latrobe Bore in the east, and is thought to extend to the west of Heywood No. 10 Bore in the Tyrendarra area. In the Mount Gambier area, the Belfast Mudstone interfingers with Flaxmans Formation to form the Mount Salt Formation. Thicknesses range from 30 feet in Sherbrook No. 1 to 2090 feet in Port Campbell No. 2.

Lithology. The mudstone is massive dark grey, with abundant glauconite (authigenic), fine disseminated pyrite, and some organic matter. Minor sandy or silty beds occur within the sequence. Fossils include fragments of ammonites, small pelecypods, gastropods, foraminifera, ostracods, and fish teeth and scales.

Age. The Belfast Mudstone is Upper Cretaceous, extending from the Ascodinium parvum Zone up to and including the Nelsoniella aceras Zone; the main portion occurs within the intermediate Deflandrea cretacea Zone (Evans, 1966b).

Relation to overlying units. The lithological change from the Belfast Mudstone to the Paaratte Formation is rapid, as shown during drilling by a sudden change in the cuttings over a short interval. Both Taylor (1964a, b) and Bock & Glenie (1965) show interfingering of Belfast Mudstone and Paaratte Formation in the northern part of the Port Campbell area.

The widespread deposition of coarse-grained sandstone of Paaratte Formation over Belfast Mudstone and Mount Salt Formation to the west heralded regressive conditions which continued into Curdies Formation time.

Environment of deposition. Mud, clay, silt, and coarser material were deposited contemporaneously with chemical precipitation in a restricted basin of deposition, in calm, slightly alkaline waters, under reducing conditions, with the formation of glauconite and sulphides. The macro- and microfaunal associations are characteristic of such an environment (Taylor, op.cit.).

Hydrocarbon occurrence. No oil staining has been observed in either the cores or cuttings of the Belfast Mudstone.

Mount Salt Formation (Unit Gg)

The Mount Salt Formation is known only in Mount Salt No. 1 (3524 + feet), Geltwood Beach No. 1 (180 feet), and Kalangadoo No. 1 (66 feet), in the Mount Gambier area. Geltwood Beach No. 1 and Kalangadoo No. 1 were probably near the edge of the main trough of deposition.

Lithology. The sediments consist of interbedded and interlaminated sandstone and mudstone (shaly in part). In Mount Salt No. 1, the uppermost 930 feet is much sandier (estimated sand/shale ratio 4:1) than the lower part (sand/shale ratio 1:1). The sandstone is a lithic greywacke, derived from metamorphic sources which have also contributed to younger units. Volcanic rock fragments have not been recorded. Cement may occur as minor siderite rhombs and patchily developed dolomite. In the latter case the porosity may be as high as 25%, with good permeability. However, the great variability in the distribution of cementing media results in erratic permeabilities laterally and vertically.

Cyclic sedimentation during deposition of the lower 2600 feet of the Mount Salt Formation produced sandstone beds 50 to 100 feet thick followed by 30 to 50 feet of argillaceous siltstone and shale. This pattern of sedimentation is not apparent in the upper, more sandy part of the Formation. The 180-foot interval corresponding to the Mount Salt Formation in Geltwood Beach No. 1 is very sandy, contains gravel, and shows no signs of cyclic sedimentation.

Age. The age of the Mount Salt Formation is determined mainly on foraminifera (Ludbrook, in ODNL, 1963a), and on spores, pollens, and microplankton (Evans, op.cit.). The age ranges from uppermost Lower Cretaceous to Upper Cretaceous within the palynological unit K2, the Ascodinium parvum Zone and part of the Deflandrea cretacea Zone. This indicates that the Mount Salt Formation is in part the time equivalent of the Waarre Formation, the Flaxmans Formation, and the Belfast Mudstone of the Port Campbell area.

Stratigraphic relations. The time break between the Eumeralla and Mount Salt Formations is probably small, but seismic data suggest that the unconformity below the Sherbrook Group extends over most of the basin.

The Mount Salt Formation grades upwards into the Paaratte Formation.

Environment of deposition. Shallow-water sedimentary structures, features indicating intermittently turbulent conditions, and cyclic deposition in the lower part of the Mount Salt Formation indicate sedimentation in a shallow sea or outer paralic zone.

The higher sandstone/shale ratio towards the top of the Mount Salt Formation suggests a regression of the sea associated with uplift of the western region at that time. However, the marked thickening of sediments in the Mount Salt area shows that as the western area was rising, a median graben, trending east-southeast, was subsiding and being filled rapidly with detritus from the marginal areas. Seismic data confirm this (Pls 8 & 9).

The reduced thickness and the granularity of sediments of the Formation in Geltwood Beach No. 1 and Kalangadoo No. 1 suggest that these wells were drilled on the margin of the graben.

Hydrocarbon occurrences. Fluorescence in cores 28 and 33 of Mount Salt No.1 was the only indication of hydrocarbons in the Mount Salt Formation: a drillstem test yielded salt water.

Paaratte Formation (Unit Gd)

The Paaratte Formation (Bain & McQueen, in FBH, 1960a) can be identified in wells throughout the Basin west of the Otway Ranges, as listed in Table 6.

Lithology. The Paaratte Formation consists mainly of sandstone and siltstone. The framework of the sandstone consists of angular to subrounded fine to very coarse-grained quartz, lithic and minor feldspar fragments. The sorting is variable, with bimodal distribution in many places.

Rounded chloritic-rock fragments and chlorite pellets are typical of the Paaratte. They have been confused with glauconite, small amounts of which may also be present. Chlorite-cemented beds occur in the Paaratte Formation and have also been noted in the Belfast Mudstone and the Mount Salt Formation.

The chloritic sandstone of the Paaratte is the 'Nullawarre Greensand Member' of the Paaratte Formation of Bock & Glenie (1965), who suggest that it represents a landward facies of part of the Belfast Mudstone. A sandstone with chlorite cement from the 4013-4393-foot interval of Port Campbell No. 4, previously correlated with the Belfast Mudstone (FBH, 1964c) is now identified as Paaratte because the composition, sorting, angularity, and maturity are similar to those of the Paaratte Formation.

The relation between cement and framework is distinctive: the carbonate cement extensively corrodes the detrital grains and contributes to the loose packing of the sandstone. Siderite rhombs have generally formed around the quartz and feldspar grains and are best developed where the grains are in contact.

TABLE 6: SUBSURFACE OCCURRENCES OF PAARATTE FORMATION

Well Name	Datum (ft above sea level)	Depths Below Datum Level (ft)	Thickness (ft)	Sand: Shale Ratio	Area
Geltwood Beach No. 1	30	2960 to 3490	530	1.6:1	
Mount Salt No. 1	86	4230 to 6520	2290	2.1:1	Mount
Kalangadoo No. 1	230	2320 to 2494	174	1.9:1	Gambier
Heathfield No. 1	244	1600 to 1680	80	2.3:1	
Nelson Bore No. 1	10	4500 to 7305T.D.	2805+		
Heywood No. 10	100	4700 to 5283	583		Tyren-
Eumeralla No. 1	167	2760 to 2960	200	1.2:1	darra
Pretty Hill No. 1	202	2370 to 2625	255	0.6:1	
Flaxmans No. 1	221	4240 to 5570	1330	0.8:1	
Port Campbell No. 1	346	4250 to 4930	680	0.5:1	Port
Port Campbell No. 2	282	5000 to 5810	810	0.3:1	
Port Campbell No. 3	210	3710 to 4230	520	3.4:1	
Port Campbell No. 4	440	4020 to 4390	370	3.3:1	Campbell
Sherbrook No. 1	480	3230 to 3590	360	0.8:1	
Fergusons Hill No. 1	651	1495 to 1955	460	1.5:1	
Latrobe No. 1	102	1525 to 1625	100		

Age. Foraminiferal studies (Taylor, 1964a) and palynological studies (Evans, 1966b) indicate that the Paaratte is Upper Cretaceous, perhaps occupying the three palynological zones *Deflandrea cretacea*, *Nelsoniella aceras* and *Xenikoon australis*. In most wells examined the bulk of the Paaratte Formation occurs in the *N. aceras* Zone.

Taylor contends that the upper beds of the Belfast Mudstone are contemporaneous with the basal Paaratte Formation.

Relation to overlying units. The Paaratte grades into the Curdies Formation, which overlies and overlaps it: the boundary probably lies between carbonate-cemented sandstone or siltstone of the Paaratte and coal stringers in the Curdies, where the environment of deposition changed.

Environment of deposition. The sediments of the Paaratte are 'marginal marine' (Taylor, 1965) or paralic, deposited in deltaic, lagoonal, and shallow neritic areas. Iron silicate, ferruginous chlorite pellets, and, in some parts, ferruginous chlorite cement were formed by flocculation of iron gels produced by climatic-pedogenic processes on a nearby landmass. Similar conditions probably recurred at different times during deposition of the Curdies and Pebble Point Formations and to a lesser extent Units Bc and C.

The sandstone was deposited in oxidizing to slightly reducing conditions with slightly alkaline water and little organic matter.

Hydrocarbon occurrence. Waxy oil was recorded in Port Campbell No. 1 (core 17, 4757 feet) (FBH, 1960a).

Porosity and permeability. The porosities of the sandstone are generally moderate to high and permeabilities are good although reduced in places by silty material and chemical cements (including chlorite). The amount of cement decreases towards the top of the sequence.

Curdies Formation (Unit Gb)

Curdies Formation (Leslie, 1966; Reynolds et al., 1966) occurs between typical Paaratte Formation and the unconformity at the base of Pebble Point Formation in fourteen subsidized wells. The main difficulties encountered in the petrological study of the Curdies Formation were that the cuttings recovered were generally loose sands, and that few cores were taken.

Lithology. The Curdies Formation is characterized by the presence of coal fragments and seams in a sequence of argillaceous sandstone and subordinate silty mudstone. The sandstone contains quartz, potash feldspar, and varying amounts of lithic fragments in a detrital matrix. The cementation of the sandstone is variable and some beds are poorly consolidated. Coal fragments and stringers are particularly abundant towards the top of the unit in wells close to the Otway Ranges (Sherbrook No. 1, Anglesea No. 1). The proportion of coal increases eastwards and in the areas of thick sedimentation at Mount Salt and Port Campbell. The cumulative thickness of coal stringers exceeds 150 feet in Anglesea No. 1; it is about 50 feet in Sherbrook No. 1, and from 60 to 70 feet in the Port Campbell and Mount Salt areas. The tentative sand/shale ratios calculated for the Curdies (Table 7) are highest in the wells nearest the main troughs of sedimentation; sandstone predominates over shale.

TABLE 7: SUBSURFACE OCCURRENCES OF CURDIES FORMATION

Well Name	Datum (ft above sea level	Depths Below Datum Level (ft)	Thickness	Sand: Shale Ratio	Area
Geltwood Beach No. 1	30	1910 to 2960	1050	1.1:1	Mount
Mount Salt No. 1	86	3270 to 4230	960	4.4:1	
Kalangadoo No. 1	230	1980 to 2320	340	1.6:1	
Heathfield No. 1	244	1217 to 1600	383	7.7:1	Gambier
Nelson Bore No. 1	10	3746 to 4500	754		
Heywood No. 10	100	4352 to 4700	348		Tyren-
Portland No. 3	16	5250 to 5574	324		
Eumeralla No. 1	167	2660 to 2760	100	2.3:1	darra
Pretty Hill No. 1	202	2160 to 2370	210	1.3:1	
Flaxmans No. 1	221	3480 to 4240	760	5.2:1	
Port Campbell No. 1	346	3380 to 4250	870	1.5:1	Port
Port Campbell No. 2	282	3750 to 5000	1250	1.7:1	
Port Campbell No. 3	210	2910 to 3710	800	2.0:1	
Port Campbell No. 4	440	2550 to 4020	1470	2.3:1	Campbell
Sherbrook No. 1	480	1930 to 3230	1300	1.3:1	
Fergusons Hill No. 1	651	849 to 1495	646	2.6:1	
Latrobe No. 1	102	1430 to 1525	95		
Anglesea No. 1	78	370 to 1816	1446	1.4:1	Torquay

In Eumeralla No. 1, coal stringers and layers cemented by siderite and some calcite occur in the Curdies Formation possibly as a result of deposition in brackish water.

Age. An Upper Cretaceous age has been determined from spores in core material from the lower part of the Curdies Formation (Flaxmans No. 1, Port Campbell No. 2).

Relation to overlying units. Curdies Formation is unconformable beneath the younger sediments, whose composition and facies show that they are derived from a subaerial, deeply weathered surface during the early Tertiary transgression.

Environment of deposition. Inner paralic to alluvial conditions prevailed in the onshore part of the Otway Basin. Thicker sands in the trough areas may be alluvium deposited in stronger energy conditions than in the intervening flats, where coal formed.

Hydrocarbon occurrences. No hydrocarbons have been reported. Organic matter in sandstone at 3650 and 4221 feet in Mount Salt No. 1 has been called 'dead oil', but Dellenbach (1964) attributes its derivation to bituminous coal.

Porosity and permeability. The Curdies Formation has high porosity and fair to good permeability.

CAINOZOIC

The Cainozoic sediments were divided into three bodies: Wangerrip Group (Unit D - Palaeocene to middle Eocene), Heytesbury Group (Unit C and Unit B-upper Eocene to Miocene), and Unit A (Pliocene to Pleistocene), which were further subdivided as shown in Table 2.

Wangerrip Group (Unit D)

The Wangerrip Group was first subdivided into the Pebble Point and Dilwyn Formations by Hawkins & Dellenbach (1963); the Dilwyn was further subdivided into Db_1 (sandstone with interbedded carbonaceous siltstone) and Db_2 (friable sandstone with compact siltstone and shale).

The Pebble Point Formation (Unit Dd) crops out at Pebble Point, near Princetown, (Baker, 1943, 1950) and at Killara Bluff in western Victoria (Kenley, 1951).

The Dilwyn Formation (Unit Db), occurs as isolated outcrops across the Basin. Sediments in a coastal section between Moonlight Head and the Gellibrand River, northwest of Cape Otway ('Dilwyn Clay' - Baker, 1953), were dated as upper Palaeocene to middle Eocene (Glaessner, 1959).

The 'Dartmoor Formation' (Boutakoff & Sprigg, 1953) in the Dartmoor and Mount Gambier areas, the 'Demons Bluff Formation' in the Torquay Area (Raggatt & Crespin, 1955) and the 'Johanna River Sands' (Thomas, 1957) in the Aire District, are thought to be correlative to the Dilwyn Formation, at least in part.

The Formations occur in all the wells examined except Casterton No. 1 and Anglesea No. 1, where the Pebble Point was not recognized.

Pebble Point Formation (Unit Dd)

Lithology. The sediments include pebbly sandstone, found chiefly in the eastern part of the Basin, pelletal oolitic sandstone, oolites, siderite rock, and siltstone. The main lithofacies variations are shown in Plate 4.

Porosity in the sandstones ranges from low to moderate, depending on diagenetic changes. The chemically cemented rocks have low porosity.

TABLE 8: SUBSURFACE OCCURRENCES OF UNITS Db (DILWYN) AND Dd (PEBBLE POINT)

Well Name	Datum (ft above sea level)	Depths Below Datum Level Db (ft)	Thicknesses (ft) Dd Db	Dd	Area
Beachport No. 1	18	900 to 1920	1020	-	
Geltwood Beach No. 1	30	960 to 1810 to 1910	850	100	
Mount Salt No. 1	86	590 to 3130 to 3270	2540	140	
Nelson Bore	10	992 to 3690 to 3746	2698	56	Mount
Kalangadoo No. 1	230	30 to 1760 to 1980	1730	220	
Penola No. 1	209	410 to 1040	630		Gambier
Tullich No. 1	272	140 to 250 to 418	110	168	
Heathfield No. 1	244	276 to 798 to 1217	522	419	
Heywood No. 10	100	1373 to 4258 to 4352	2885	94	
Portland No. 2	110(1)	2974 to 4719	1745	-	
Portland No. 3	16(1)	2862 to 5050 to 5250	2188	200	Tyren-
Eumeralla No. 1	167	1270 to 2530 to 2660	1260	130	darra
Pretty Hill No. 1	202	1200 to 2030 to 2160	730	130	
Flaxmans No. 1	221	2213 to 3320 to 3480	1107	160	
Port Campbell No. 1	346	1510 to 3300 to 3380	1790	80	
Port Campbell No. 2	282	1230 to 3650 to 3750	2420	100	
Port Campbell No. 3	210	1300 to 2740 to 2910	1206	170	Port
Port Campbell No. 4	440	1300 to 2390 to 2550	1090	160	
Sherbrook No. 1	480	560 to 1710 to 1930	1150	220	Campbell
Fergusons Hill No. 1	651	13 to 670 to 849	657	179	
Anglesea No. 1	78	13 to 370	357	-	Torquay

(1) Figures taken from Glenie & Reed (1961).

Age. The Pebble Point Formation is of middle to upper Palaeocene age (BMR, 1966, p.80; Ludbrook *in* ODNL, 1963a; Harris, 1965; Taylor *in* FBH, 1963a, 1964a; and McGowran, 1965).

Relation to overlying unit. The sediments of the Pebble Point Formation pass conformably into the overlying siltstone and silty sandstone of the Dilwyn Formation, and fossil dating suggests continuous deposition.

Environment of deposition. The formation was deposited in shallow water during a marine transgression. The rounded detrital grains and ooliths are indicative of high energy currents. The waters were supersaturated in calcium carbonate and a carbonate cement was precipitated and carbonate ooliths formed; at times reducing conditions prevailed, and siderite and phosphate were precipitated.

The pebbly sandstone, which lacks pellets but contains some ooliths and minor dolomite cement, is a shoreline facies equivalent of the oolitic sandstone.

Hydrocarbon occurrences. No hydrocarbons are known in the Pebble Point Formation. Sands with good porosity and permeability are found in Mount Salt No. 1 and Flaxmans No. 1, but sands in other wells appear to be of low permeability.

Dilwyn Formation (Unit Db)

The Dilwyn Formation has been found in all the subsidized wells studied except Casterton No. 1; and in several unsubsidized wells. Table 8 lists the subsurface occurrences.

Lithology. The formation includes sandstone, carbonaceous sandy siltstone, and shale, subdivided into two subunits, Db_1 and Db_2.

Subunit Db_2 (lower) is a succession of argillaceous dark brown to grey sandstone, siltstone, and shale. The siltstone and shale are brown, compact, sandy and micaceous, and contain finely disseminated carbonaceous matter.

Subunit Db_1 differs from Db_2 in the increased content of finely divided carbonaceous matter and variation in grainsize. The rock types are sandstone with subordinate siltstone.

The clay content of the Dilwyn Formation decreases from bottom to top, and grainsize increases correspondingly; the carbonaceous content increases from bottom to top; electric logs indicate cyclic alternation of siltstone and sandstone (observed also from cuttings).

The porosity and permeability are generally high and increase towards the top of the sequence.

Minor variations occur across the Basin. In Eumeralla No. 1 and Pretty Hill No. 1 an increase in the amount of dolomite and siderite-cemented sandstone occurs in subunit Db_2.

Age. The Dilwyn Formation is thought to range in age from Palaeocene to middle Eocene (BMR, 1966, p.84).

Relation to overlying unit. The top of the Dilwyn Formation is marked by a break, present throughout the Basin, which may be either an unconformity, as observed in the Nelson bore, or non-depositional. In most of the wells, Dilwyn Formation is overlain by Unit Bc sediments; but in Tullich No. 1, Unit Ab rests unconformably on Dilwyn Formation, and both Sherbrook No. 1 and Anglesea No. 1 wells spudded into the Dilwyn Formation.

Environment of deposition. Subunit Db_2 was deposited in a paralic environment. Marine deposition is shown by carbonate-cemented sandstone, glauconite, and isolated marine fossils; small amounts of carbonaceous matter occur in the sediments, possibly in pro-delta deposits.

Db_1 was deposited during regression under predominantly deltaic conditions interrupted by minor marine incursions. Abundant carbonaceous material, lignitic and coaly lenses, plant remains, burrows, pyrite, phosphatic fragments, and glauconite, indicate that the waters were generally reducing or neutral.

The alternation of coarse and fine carbonaceous sediments may be a result of stream migration across deltaic flats.

Hydrocarbon occurrences. Cores of the Dilwyn Formation from Mount Salt No. 1 showed some fluorescence of unknown origin.

Heytesbury Group (Units B and C)

Unit B, defined in the Nelson Bore (Hawkins & Dellenbach, 1963), is the equivalent of the Glenelg and Heytesbury Groups of other authors and is here subdivided into Unit C and Units Bc and Bb.

Unit C

Unit C is known in bores at Kingston (Ludbrook, 1963) and crops out in the Port Campbell, Aire, and Torquay areas, in coastal sections around the flanks of the Otway Range structure. Lithofacies changes occur between the western half of the Basin, where only limonitic sandstone was deposited, and the Port Campbell area, where marl is present above the sandstone (see Pl. 5).

TABLE 9 : SUBSURFACE OCCURRENCES OF UNIT C

Well Name	Datum (ft above sea level)	Depths Below Datum Level (ft)	Thickness (ft)	Area
Geltwood Beach No. 1	30	910 to 960	50	
Mount Salt No. 1	86	510 to 590	80	Mount
Nelson Bore	10	812 to 992	180	
Tullich No. 1	272	70 to 140	70	Gambier
Heathfield No. 1	244	152 to 276	124	
Heywood No. 10	100	1335 to 1373	38	
Portland No. 2	110	2964 to 2974	10	Tyren-
Portland No. 3	16	2823 to 2862	39	
Eumeralla No. 1	167	1200 to 1270	70	darra
Pretty Hill No. 1	202	1220 to 1300	80	
Port Campbell No. 1	346	1150 to 1510	360	
Port Campbell No. 3	210	1280 to 1534	254	
Port Campbell No. 4	440	1012 to 1300	288	Port
Sherbrook No. 1	480	250 to 560	310	Campbell

Lithology. The unit consists of fine-grained sandstone grading into very coarse-grained sandstone; in the Nelson Bore a conglomerate 6 feet thick occurs at the base. Chamosite and limonite pellets are common throughout and the cement is mostly dolomite.

The high percentage of dolomite cement is probably related to a primary carbonate cement which has been changed diagenetically. The pellets are thought to have been formed by slight current action on a fine-grained precipitate.

Purplish brown glauconitic marl, containing limonite and glauconite pellets and spots of gypsum associated with pyrite, was encountered in Port Campbell No. 1.

Age. The basal limonitic sandstone facies, occurring throughout the basin, is generally thought to be of upper Eocene age (to possibly middle Eocene in the west) except in the Nelson Bore area, where an Oligocene fauna is present; a conformable marl facies (with glauconite and limonite) in the Port Campbell area, of Unit 3 (upper Eocene-Oligocene transition) zone of Carter (1958b, 1964).

Relation between Units C and B. A time break occurs between Units C and B: it is present throughout the basin.

Plate 5 shows that Unit B is much more constant in thickness than C, and suggests the possibility of some erosion of C following broad uplift between C and B times. In the Port Campbell area Unit C is much thicker than in the west; the time break is not great. Erosion may be greater in the west, where the marl facies is generally absent.

Environment of deposition. The limonitic sandstone facies reflects a period when the sea transgressed across a still unstable landmass. A basal conglomerate at the bottom of this sequence in the Nelson Bore may be derived from the reworking of an older, possibly Eocene, conglomerate. In the sandstone, pellets of limonite, hematite, and goethite and rounded grains suggest deposition under high-energy conditions in shallow oxygenated waters. Conditions were quieter during the precipitation of the carbonate of the marl facies in the Port Campbell area.

Hydrocarbon occurrences. There were no indications of hydrocarbons.

Porosity and permeability. The basal sands have good porosity and permeability, but have probably been flushed in the onshore area. The marl at the top of the subunit in the Port Campbell area may be important offshore as a cap-rock.

Unit Bc and Unit Bb

Where present in the subsurface, Unit Bc, a glauconitic limestone facies, is conformable with the overlying Unit Bb, and the two units are treated together. The distribution of the units is shown in Plates 5 and 6, and listed below in Table 10.

The Clifton Formation (Teichert, 1947; Baker, 1950, 1953) of the Port Campbell area, the Calder River Limestone of the Aire District (Carter, 1958b), and the Jan Juc Formation (Raggatt & Crespin, 1955) in the Torquay area are correlated with Unit Bc. The Compton Conglomerate, which crops out in Knights Quarry in the Mount Gambier area, and the subsurface Nelson Formation of the Tyrendarra area are also thought to be correlatives.

Unit Bb includes: the Gambier Limestone, which has been defined from outcrop in the Mount Gambier area (Boutakoff & Sprigg, 1963); the Port Campbell Limestone (Baker, 1953) and the Gellibrand Clay, which crops out northwest of Point Ronald; the Heywood Marl (Glenie & Reed, 1961) and the Puebla Formation (Raggatt & Crespin, 1955) with a type section between Bird Rock and the mount of Spring Creek. The Fishing Point Marl and Upper Glen Aire Clays (Carter, op.cit.) are correlatives of Bb in the Aire district.

Lithology. Unit Bc consists of glauconitic marly limestone, sandstone, and sandy limestone containing glauconitic pellets. In all these rocks, oxidized glauconite, limonite, iron oxide pellets and ooliths, and reworked limonitic rock fragments may occur.

Unit Bb contains a marly limestone or marl containing spicules, and a polyzoal limestone with chert. An increase in the proportion of marl in the Tyrendarra and Port

TABLE 10 : SUBSURFACE OCCURRENCES OF UNIT Bc AND UNIT Bb

Well Name	Datum (ft above sea level)	Depths Below Datum Level (ft) Bc	Bb	Thickness (ft) Bc	Bb	Area
Beachport No. 1	18		300 to 775		475	
Geltwood Beach No. 1	30	890 to 910	60 to 890	20	830	Mount
Mount Salt No. 1	86	480 to 510	16 to 480	30	464	
Nelson Bore	10		0 to 812		812	Gambier
Penola No. 1	209		35 to 250		215	
Heywood No. 10	100	1288 to 1335	12 to 1288	47	1276	
Portland No. 2	110	2841 to 2964	115 to 2841	123	2726	Tyren-
Portland No. 3	16	2770 to 2823	42 to 2770	53	2728	
Eumeralla No. 1	167	1110 to 1200	13 to 1110	90	1097	darra
Pretty Hill No. 1	202	1160 to 1220	50 to 1160	60	1110	
Flaxmans No. 1	221		15 to 1920		1905	
Port Campbell No. 1	346	1050 to 1150	9 to 1050	100	1041	
Port Campbell No. 2	282		16 to 782		766	Port
Port Campbell No. 3	210	1248 to 1280	15 to 1248	32	1233	
Port Campbell No. 4	440	964 to 1012	13 to 964	48	951	Campbell
Sherbrook No. 1	480	210 to 250	13 to 210	40	197	
Latrobe No. 1	102	160 to 200		40		

Campbell areas is accompanied by a corresponding decrease in the polyzoal limestone. There is little evidence of chert in the limestone sequence in the eastern part of the basin, but secondary chert is well developed in the Mount Gambier area.

Thickness variations are most marked in the Tyrendarra area between Portland No. 3 and Eumeralla No. 1 (Pl. 6).

Age. The age of Unit Bc is thought to be uppermost Eocene (unit 3 zone of Carter) to Oligocene, whereas Unit Bb ranges in age from Oligocene to Miocene.

Relation of Unit Bb to overlying units. The overlying sediments are either Pliocene or Recent and are unconformable upon Bb. Most of the wells, especially in the Port Campbell area, spudded in Unit Bb.

Environment of deposition. The glauconitic marly limestone facies of Bc was deposited after a marine transgression over a shallow shelf area. The temperature and salinity were suitable for supporting calcareous organisms. Although calcium and magnesium carbonates were precipitated, the pH and Eh must have been near neutral at times for glauconite to form. The generally low detrital content indicates that sedimentation was taking place on a stable shelf area adjoining a low-lying landmass.

Unit Bb sediments were deposited under open-shelf, nearshore conditions. Sandy limestone gives way to marl and clean limestone towards the top of the sequence.

Hydrocarbon occurrences. No indications of hydrocarbons have been observed.

Unit Ab

Unit Ab, as described from Heathfield No. 1 (Hawkins, 1965), corresponds to the Normanby Group (Boutakoff & Sprigg, 1953).

The Group includes the Whalers Bluff Formation, which consists of fossiliferous marl, clay, and calcarenite.

Casterton No. 1, Heathfield No. 1, Tullich No. 1, and Kalangadoo No. 1 contain sediments of Unit Ab; Penola No. 1 is also thought to contain them. Glenie & Reed (1961) have recognized correlatives in Portland No. 1 and No. 3 wells.

Lithology. Unit Ab is composed of yellowish orange and light to medium brown sandy calcarenite, biocalcarenite, and sandy limestone. The cement is finely recrystallized calcite, siderite, and dolomite.

Clay and shelly marl which occur in the Maritime Member in Portland Nos 2 and 3 wells (Glenie & Reed, 1961) are not present to the north in the Heathfield - Tullich area.

Age. Unit Ab extends from Pliocene to Pleistocene; the Portland sequence appears to be older than the Heathfield.

Relation to overlying sediments. Unit Ab is overlain conformably by sand and clay of Quaternary age. In Portland No. 2, Ab is overlain by basalt.

Environment of deposition. From the rounded and very coarse nature of the quartz grains and bioclastics, the lack of clay matrix, and the presence of carbonate cement, the upper sediments of Ab appear to have been deposited in a shallow sea in a high-energy environment; earlier, in the Portland area, quieter conditions prevailed.

Hydrocarbon occurrences. No hydrocarbon occurrences are known despite high porosity and permeability in the sandy sections.

TABLE 11: DISTRIBUTION OF PALYNOLOGICAL MARKER FOSSILS

	PALYNOLOGICAL UNIT											
	TERTIARY	'D. pellucida'	X. australis	N. aceras	D. cretacea	A. parvum	K2b	K2a	K1d	K1b-c	K1a	J-K and H
Nothofagidites emarcida												
Nothofagidites cf. deminuta												
Dacrydiumites florinii												
Triorites edwardsii												
Phyllocladidites mawsonii												
Tricolpate/triporate pollen grains												
Laevigatosporites ovatus												
Trilobosporites trioreticulosus												
Coptospora paradoxa												
Crybelosporites striatus												
Dictyotosporites speciosus												
Cyclosporites hughesi												
Murospora florida												
Cicatricosisporites australiensis												
Dictyotosporites complex												
Lycopodiumsporites circolumenus												
Foraminisporis wonthaggiensis												
Klukisporites scaberis												
Lycopodiumsporites spp.												
Baculatisporites comaumensis												
Laricoidites sp.												
Deflandrea pellucida												
Xenikoon australis												
Nelsoniella aceras												
Gymnodinium nelsonense												
Amphidiadema denticulata												
Deflandrea cretacea												
Hystrichosphaeridium heteracanthum												
Deflandrea acuminata												
Palaeohystrichophora infusorioides												
Hystrichodinium oligacanthum												
Odontochitina operculata												
Ascodinium parvum												
Acritarcha spp.												

PALYNOLOGY

by P.R. Evans

Many reports on the microfloras of specific wells in the Otway Basin have been compiled. Most of them are unpublished, but are available as either BMR records or appendices to subsidized well-completion reports. From these data Evans (1966b) compiled a tentative biostratigraphic framework from which the relative ages of sediments within the basin were assessed.

Douglas (1962) discussed three microplankton zones in the Upper Cretaceous and Tertiary of the Otway Basin. Evans (1962) recognized four microplankton zones in the Upper Cretaceous and subsequently added another zone transgressing the Upper Cretaceous-Tertiary boundary. Dettmann (1963) defined three microfloral assemblages and Evans (1966b) informally named five palynological divisions of the Lower Cretaceous. The zones and divisions are shown in Table 11 with the ranges of a number of selected species. Lists of associated species may be found in references in Dettmann (op. cit.) and Evans (op. cit., and BMR, 1966). The relation between zones and the formations of the Otway Basin are shown in Plates 3A and 3B.

The subsidized wells Casterton No. 1, Kalangadoo No. 1, Pretty Hill No. 1, and Fergusons Hill No. 1 have penetrated the Mesozoic of the Otway Basin to enter Palaeozoic (?) basement. Only one sample of this basement, from Kalangadoo No. 1, core 14, 7069 feet, has been examined in the BMR for a spore/microplankton content, but it yielded only highly carbonized residues.

Casterton No. 1 probably penetrated the oldest Mesozoic sediments encountered onshore in the Basin, the unnamed Unit T. The association of the long-ranging forms *Baculatisporites comaumensis* and *Lycopodiumsporites* sp. in core 18 within Unit T indicates an age no older than Jurassic, but there is insufficient evidence to indicate which part of the Upper Mesozoic is represented.

Another palynological assemblage which appears to be unique in the Otway Basin occurs in core 14 at 6396 feet in Casterton No. 1. The relatively abundant microflora and rare acritarchs suggest a Lower Cretaceous or Upper Jurassic, but no older than about Tithonian, age. The sediments at this depth form part of the Geltwood Beach Formation (Unit P); all other samples from that formation have yielded younger, K1, assemblages.

Lower Cretaceous

Unit K1a

The base of Unit K1a, the oldest Cretaceous unit recognizable in the Otway Basin, is marked by the first appearance of *Cicatricosisporites australiensis* (Cookson), *Cyclosporites hughesi* (Cookson & Dettmann), and *Dictyotosporites speciosus* (Cookson & Dettmann). The top of the unit is marked by the last appearance of *Murospora florida* (Balme). K1a incorporates Dettmann's (1963) *stylosus* Assemblage and the lower part of the *speciosus* Assemblage.

Beds of K1a age begin in the Geltwood Beach Formation and possibly in the 'Pretty Hill sandstone' (Unit R), and end in the Eumeralla Formation (Unit M). The top of K1a cannot be determined in those sections where *M. florida* is apparently missing.

Unit Kib-c

Unit Klb-c includes the continued appearance of Cicatricosisporites australiensis and Dictyotosporites speciosus; its upper limit is marked by the first appearance of Crybelosporites striatus. The previous division into Klb and Klc, based on the ranges of D. speciosus and C. hughesi, cannot be upheld and Klb-c is now used (Evans, in BMR, 1966, p.118). It forms a portion of Dettmann's speciosus Assemblage, younger than that containing M. florida.

The lowest stratigraphic occurrence of Klb-c is in core 11 at 6120 feet in Kalangadoo No. 1; this is in the Geltwood Beach Formation. The unit ranges from the upper part of the Geltwood Beach Formation to the lower part of the Eumeralla Formation. This is the same as the range of Kla and suggests some form of diachronism between the two formations in the Geltwood Beach to Casterton region.

Unit Kld

Unit Kld is within the uppermost part of Dettmann's speciosus Assemblage. Its base is marked by the first appearance of Crybelosporites stratus (Cookson & Dettmann), its top by the first appearance of Coptospora paradoxa (Cookson & Dettmann) which characterizes Unit K2. D. speciosus occurs throughout Kld.

Beds with Kld assemblages are confined to the Eumeralla Formation, and appear to extend throughout the onshore part of the Otway Basin from Beachport No. 1 in the west to Fergusons Hill No. 1 in the east.

The 'Heathfield Sand' (Brown, 1965) occurs in Heathfield No. 1 over the interval 4115 to 4144 feet and is just above, or within, the Kld zone (known from core 10, 4146 feet). The 'Heathfield Sand' is suspected to be at the base of Kld (or in Klc) in Penola No. 1. However, it is developed towards the top of Kld in Casterton No. 1, where a marked expansion is noted in the thickness of Kld. This supports Brown's idea of an unconformity at the base of the 'Heathfield Sand', and suggests that considerable erosion took place at that time in the Penola - Heathfield area.

Unit K2a

Dettmann (1963) took the point of first appearance of Coptospora paradoxa as the start of the paradoxa Assemblage. This is chosen from the base of K2. Dettmann also noted that the ranges of D. speciosus and C. paradoxa overlap in some samples. This overlap is slight in terms of thickness of section and hence forms a useful marker, which is denoted as Unit K2a.

Only single samples in any one section have demonstrated this overlap: Penola No. 1, core 9, 2790-98 feet; Beachport No. 1, core 9, 3665-75 feet; Flaxmans No. 1, core 40, 10,492-502 feet; and Fergusons Hill No. 1, core 18, 6555-70 feet. The zone could be present in Kalangadoo No. 1, Casterton No. 1, Geltwood Beach No. 1, Eumeralla No. 1, and Pretty Hill No. 1, although not confirmed by palynology.

Unit K2b

The range of Coptospora paradoxa beyond its overlap with D. speciosus and before the introduction of tricolpate/triporate angiospermous pollens characterizes Unit K2b. Dettmann recorded several species characteristic of the paradoxa Assemblage, including Trilobosporites trioreticulosus Cookson & Dettmann, which may also be regarded as characteristic of K2b. Dettmann (1963) and Evans (1963) noted the first appearance of angiosperm pollen grains in the Winton Formation of the Great Artesian Basin. In Innamincka No. 1 Well, angiosperm pollen grains are associated with the paradoxa Assemblage, but it is better to regard their introduction as another marker horizon and restrict K2b to below that level. The top of K2b in the Beachport-Casterton area is conveniently marked by an unconformity at the top of lithological Unit M - Eumeralla Formation. In the eastern portions of the basin, the first angiosperm pollen grains occur within the Waarre Formation in Port Campbell No. 1, core 23, 5700-08 feet, an horizon which could be thought of as close to the top of Unit K2b. Thus K2b occurs within the Eumeralla Formation in the western Otway Basin, and in the Eumeralla and the lower but major portion of the Waarre Formation in the east.

Upper Cretaceous

Although angiosperm pollen grains have been recorded from the Upper Cretaceous sections, particularly in the east, few of them are described, and additional work is required before much stratigraphic use is made of them. The Upper Cretaceous microplankton are better documented and afford a means of biostratigraphic division of the containing beds. The first appearance of angiosperm pollen grains is taken as a marker for the base of the Upper Cretaceous. Microplankton, including dinoflagellates, are well established where this takes place in the Waarre Formation (=Unit J). The incoming of angiospermous pollen seems to coincide with the introduction of the oldest recognizable microplankton zone of Ascodinium parvum.

Ascodinium parvum Zone+

In the Port Campbell area, A. parvum is associated with a variety of microplankton in the top of the Waarre Formation and in the Flaxmans Formation (Unit Gf), thought to be about Cenomanian in age. An abundant microplankton assemblage referable to the A. parvum Zone occurs in Geltwood Beach No. 1, core 8, 3773-93 feet, particularly at 3774 feet, at the top of the Eumeralla Formation (M). The Zone also appears in the Mount Salt Formation (Gg) in Kalangadoo No. 1 Well. In spite of lithological evidence for an unconformity between the Waarre Formation and Eumeralla Formation in the eastern part of the basin it appears that the Waarre Formation and possibly the Flaxmans Formation were formed contemporaneously with at least the uppermost parts of the Eumeralla Formation and the Mount Salt Formation in the west during A. parvum Zone time.

Deflandrea cretacea Zone*

The next recognizable unit is the Zone of Deflandrea cretacea Cookson, taken from the beginning of the range of D. cretacea to where it eventually overlaps with the range of the succeeding zone fossil Nelsoniella aceras. Thus defined, the zone occurs in the upper parts of the Belfast Mudstone (= Unit Gf), but the relationship of the A. parvum and D. cretacea Zones is not clear. Cuttings from the Flaxmans Formation in Port Campbell No. 1, 5600-10 feet, yielded D. cretacea, but the oldest record from a core sample is much higher in the sequence from core 21, 5223-31 feet, and similarly in Flaxmans No. 1, from core 16, 5959-68 feet. D. cretacea may first appear some time later than the last appearance of A. parvum, so that an unclassified gap occurs in the sequence. A similar problem occurs below the first appearance of D. cretacea in the western portion of the basin. D. cretacea was not found in Mount Salt No. 1 below core 20, 5490 feet, in the N. aceras Zone, but fossils which could represent the D. cretacea Zone, or beds younger than the A. parvum Zone, were present in core 21 and below; Evans (in BMR, 1966b) concluded that more palynological study was required of this section in the Mount Salt area. On available evidence, the D. cretacea Zone in the western part of the Otway Basin extends upwards into the Paaratte Formation.

+ Symbolized by 'A.p.' on Plates 3A, 3B.

* Symbolized by 'D.c.' on Plates 3A, 3B.

Nelsoniella aceras Zone**

The Deflandrea cretacea Zone is succeeded by the Zone of Nelsoniella aceras Cookson & Eisenack, taken from the horizon of first appearance of N. aceras to the first appearance of Xenikoon australis. The pollen complex associated with the N. aceras Zone includes the first appearance of Triorites edwardsii Cookson & Pike (Port Campbell No. 1, core 17, 4758-60 feet), Phyllocladidites mawsonii Cookson (Geltwood Beach No. 1, core 7, 3632 feet).

In the Port Campbell area, the N. aceras Zone occurs in the lower part of the Paaratte Formation, possibly extending to the Belfast Mudstone. In the western region, N. aceras has been recorded from the Paaratte Formation in Mount Salt No. 1 and the Nelson Bore. Its possible range in the Nelson Bore is extended downwards to at least 6233 feet, because of the presence of Gymnodinium nelsonense at that level (Cookson, 1956a). However, in contrast to its distribution in the eastern wells, the N. aceras Zone does not extend down to or beyond the base of the Paaratte Formation in the Mount Salt/Nelson area.

Xenikoon australis Zone +

Xenikoon australis, first described by Cookson & Eisenack (1958) from Campanian sediments in the Carnarvon Basin, occurs in an appropriately high position in the Otway Basin. Its full range in the basin has not yet been determined because of the lack of samples, but for the present, the base of the Zone of Xenikoon australis is taken at the point of first appearance of X. australis, and all points of occurrence of that fossil are included within the zone. Nothofagidites cf. deminuta (Couper) and Dacrydiumites florinii Cookson & Pike make their first appearance within or just before the X. australis Zone.

An upper portion of the Paaratte Formation and at least two thirds of the Curdies Formation (in Port Campbell No. 1) represent the X. australis Zone. The zone fossil has been detected as far west as Mount Salt No. 1, but could only be found in core 14, 4538 feet. A possible representative of that zone was sampled in Heathfield No. 1, core 2, 1378-93 feet, from the Curdies Formation, where a fragmentary specimen, possibly referable to X. australis, was noted.

'Deflandrea pellucida Zone'

Lack of information from above the X. australis Zone precludes both determination of a satisfactory top to the zone and additional subdivision of the Curdies Formation. Douglas (1962) identified 'a post-Mesozoic, early Tertiary zone of large "D. bakeri" type micro-organisms'. Deflandrea bakeri was first described by Deflandre & Cookson (1955) from outcrops of the Pebble Point Formation. They recognized at the time a variety, D. bakeri cf. pellucida, in the Nelson Bore, core at 3874 feet, and in the Pebble Point Formation outcrop. Cookson & Eisenack (1958) raised cf. pellucida to specific rank after recognizing it in the Korojon Calcarenite of Campanian-Maestrichtian age in the Carnarvon Basin. Douglas apparently includes occurrences of both bakeri and pellucida in his 'D. bakeri' type zone, but in fact records D. bakeri only from Heywood No. 10, 4300 feet *, which Leslie (1966) includes in the 'Bahgallah Formation'. Apart from Deflandre & Cookson's record of D. pellucida from Nelson, Douglas reported ?D. pellucida from Belfast No. 4, 4074-6 feet (Paaratte Formation acc. Weegar, 1960a) and Port

** Symbolized by 'N.a.' on Plates 3A, 3B.

+ Symbolized by 'X.a.' on Plates 3A, 3B.

* Symbolized by 'D.k.' on Plate 3A.

Campbell No. 2. Douglas indicated in his section that his 'D. bakeri' type zone was represented in the latter well at 4800 feet (low in the Curdies Formation), although in his text he records D. cf. pellucida from 5910-11 feet (top of the Belfast Mudstone), probably below the level of the N. aceras Zone. It appears that the 'D. bakeri' type zone is not an effective stratigraphic marker. However, the one identification of the holotype of D. pellucida high in the Curdies Formation in the Nelson Bore, coupled with Cookson & Eisenack's determination of the species in the Carnarvon Basin in beds stratigraphically younger than those with Xenikoon australis (which is no younger than Campanian) suggests that an uppermost division of the Upper Cretaceous of the Otway Basin might be recognized by a Zone of Deflandrea pellucida*, represented by that part of the range of D. pellucida prior to the introduction of a more typical Tertiary assemblage. Such a zone would incorporate the upper part of the Curdies Formation.

Cretaceous-Tertiary Boundary

Harris (1965) recognized a Triorites edwardsii Assemblage in the outcrop of the Pebble Point Formation and in part of the overlying 'Dilwyn Clay' which he refers to the middle Palaeocene foraminiferal Zone of Globorotalia pusilla pusilla (McGowran, 1965). McGowran implied that lowermost Palaeocene is not represented in the Otway Basin. Studies have shown that the presence of the nominate species of the T. edwardsii Assemblage Zone may not be a suitable means of distinguishing basal Tertiary from uppermost Cretaceous sediments, and for the present the boundary between the Cretaceous and Tertiary, at least in the Port Campbell area, is considered to be at the unconformity between the Curdies Formation and the Pebble Point Formation.

In the Torquay area, the Eastern View Coal Measures of Anglesea No. 1, identified on lithology as Unit Gb and correlated with the Curdies Formation, are mainly representatives of the T. edwardsii Assemblage Zone, and the position of the Cretaceous-Tertiary boundary cannot be accurately determined.

*Symbolized by 'D.p.' on Plate 3A.

GEOPHYSICS

by A.L. Bigg-Wither and R.P.B. Pitt

This section deals mainly with the significance of the results available to the end of 1965. Certain magnetic features are shown in the subsurface structure map (Pl. 7) of this report. Gravity contours covering the onshore part of the Basin have been taken from BMR Geophysical Branch compilations and from the work by Richards (1956). Three seismic reflectors, which conform closely with basin-wide unconformities, were contoured and isochron contour maps were prepared of the intervals between the horizons (Pls 8 to 12). Dip information from discontinuous deeper reflections was used to obtain the fold directions which are incorporated in the subsurface structure map of the Otway Basin (Pl. 7).

Aeromagnetic surveys

In the area offshore, opposite the Padthaway Ridge, aeromagnetic results suggest that a broad graben with sediments to more than 4000 feet extends north towards The Coorong; local anomalies caused by basement variations are also evident (HEPL, 1965b). Deepening of sediments is indicated by seismic surveys in this area, which is regarded as an extension of the Otway Basin. The trend of the gravity low to the north of Kingston may be associated with an extension of the deep sediments onshore; a corresponding depression is shown in the aeromagnetic interpretation. Alternatively, the gravity minimum could be caused by granite known to intrude the Padthaway area. If the section thickens in this area, Permian sediments, some of which are marine, could extend into the area from known onshore occurrences.

The more important aeromagnetic anomalies occurring in the Otway Basin south of the offshore extension of the Padthaway Ridge are shown on Plate 7. Anomaly 8 - 4 is a broad feature thought to be associated with basic igneous basement.

Aeromagnetic and seismic evidence for Anomaly 8 - 5 suggests vulcanicity in the Sherbrook Group. Seismic evidence shows Tertiary sediments at this anomaly disturbed only by faulting; aeromagnetic evidence indicates basic intrusives at about 7000 feet, i.e. in pre-Sherbrook Group sediments. Perhaps the vulcanicity was penecontemporaneous with that in the Casterton area in the Upper Jurassic or Lower Cretaceous.

One of the most prominent regional features shown by the total magnetic intensity contours is the broad minimum off the coast of South Australia trending east-southeast and extending onshore south of Mount Gambier. It may indicate a trough with more than 10,000 feet of sediments. The same trend persists across the border into Victoria towards Portland, where seismic surveys indicate similar troughs. A broad magnetic minimum trending northwest occurs southeast of Portland and may be linked with the preceding one, suggesting a continuous trough which has been disrupted by faulting along trends southwest from the 'Dartmoor Ridge' (see Gravity Section). The southern side of the trough is indicated in the total magnetic intensity contours by a very gradual rise to the south along the coast of South Australia.

Aeromagnetic interpretation indicates more than 18,000 feet of sediments in a second trough between Mount Gambier and Millicent (CGG, 1965). It is separated from the first, at least in the northwestern part, by a spur of shallower basement extending southeast from the Beachport Area.

Extensions of two lines beyond the edge of the continental shelf (HEPL, 1965b) show only a smooth regional increase in the value of the total intensity contours, south of the magnetic low anomaly in southern South Australia, of the order of 60 gammas. This may be compared with rises across other continental shelves of more than 300 gammas-as in the Atlantic coast of North America (Heezen et al., 1959).

Farther east, Anomalies 14 - 1, 2 and 5, and 15 - 1 and 2, may indicate pre-Sherbrook Group volcanic activity, or be associated with the 'Older (Oligocene) Volcanics'. Anomaly 14 - 5 coincides with a strong positive gravity anomaly at Cape Otway, and may be caused by shallow basement or by a deep volcanic body.

Basement is shallow in most of the area east of the Otway Ranges, and northwest from King Island. The main trend of the strong magnetic features is meridional, similar to the regional basement trends. The eastern side of the area is marked by strong linear gradients in alignment with the onshore Selwyn Fault to the north, and may represent the eastern margin of the Otway Basin.

BMR has recently completed some twenty east-west high-altitude aeromagnetic traverses across Tasmania, which were extended offshore east and west across the continental shelf and slopes (Finney & Shelley, 1967). The western offshore area is magnetically flat, similar to the southern parts of the Otway Basin, although some troughs were delineated. The survey also showed that the magnetic basement is generally shallow, particularly in the northwestern part. Apparently the Precambrian block of northwestern Tasmania extends offshore to the north-northwest, perhaps bordered by Cambrian rocks similar to those onshore.

Gravity surveys

Gravity surveys have supplied significant information on the northwestern, northern and eastern margins of the basin. The northwestern and northern limits are indicated by a prominent zone of steep gravity gradients which may be the expression of a faulted zone extending northeast from Guichen Bay in the west to a few miles north of Lucindale, and thence west of Naracoorte via Dergholm to Casterton. Southeast of Casterton, the zone may swing east-northeast through Merino, then southeast past Hamilton. Steep gradients aligned approximately westerly through Geelong may correspond to west-trending faults known to occur in that area. The eastern limit of the basin is a zone of steep gradients coincident with the Selwyn Fault.

In southeastern South Australia both aeromagnetic and gravity coverage show a general correspondence between the zones of steep gradients and faulting. An exception occurs southeast of Cape Jaffa, where steep gravity gradients trend southwesterly across the easterly trend of the aeromagnetic fault interpretation.

The fault zone which forms part of the northwestern limit of the Basin is followed to the south by the 'Cape Dombey Gravity Trough' which extends between Cape Dombey and Lucindale. Calculations made on the assumption of a density contrast of 0.3 gm/cc between basement and sediments show a basement depth of approximately 10,000 feet.

A marked change in structural trend occurs at the northeastern end of the 'Cape Dombey Gravity Trough'. Adjacent structures trend southeasterly, forming the 'Lucindale-Penola Gravity Terrace', bounded on both northern and southern sides by faulting according to gravity and aeromagnetic evidence. Structure on the terrace is indicated by a succession of gravity high and low anomalies. Contours on magnetic basement agree with the structural trends indicated by gravity in this area and magnetic depth estimates range from 3000 to 8000 feet.

A southeast-trending gravity low southwest of the 'Lucindale-Penola Gravity Terrace' is thought to indicate a deep trough of sediments, the 'Penola Trough'. This is confirmed by seismic and aeromagnetic data.

The area southeast of the 'Cape Dombey Trough' and west of the 'Penola Trough' appears to contain less sediments than adjoining areas and the sediments become thinner to the south towards a gravity high around Beachport.

Southwest of the 'Penola Trough' and southeast of Beachport, the gravity interpretation suggests a broad area of southeasterly-trending sediments somewhat thinner than in the 'Penola Trough'. However, the pattern of anomalies does not reflect the aeromagnetic and seismic indications of zones of deep sediments. Only isolated lows of small amplitude occur on a gentle gradient rising towards the coast. Three possible explanations of the divergence between gravity and seismic-aeromagnetic interpretations have been considered (Bigg-Wither, in BMR, 1966):

(i) an isostatic anomaly;

(ii) a rise in the base of the Otway Basin sedimentary sequence from inland towards the coast;

(iii) a thinning of the sialic crust from inland towards the continental edge.

The lack of gravity control near the coast and offshore limits interpretation.

The southeasterly trend of gravity anomalies from South Australia into western Victoria is interrupted by the 'Dartmoor Gravity Ridge' which extends to the south-southwest from Merino. It may reflect either a regional basement trend or thick, shallow basalts (surface flows have occurred in this area). The strong positive anomaly near Cape Bridgewater to the south of the 'Dartmoor Gravity Ridge' is supported by a magnetic anomaly and thought to be associated with basalt intrusion and extrusion.

Bouguer anomalies to the east of the 'Dartmoor Gravity Ridge', in the Tyrendarra area, are of small amplitude and long wavelength, suggesting thick sediments throughout. Seismic surveys and drilling have shown thick section locally and variation in basement relief.

The 'Warrnambool Ridge' is a prominent positive anomaly with a south-southwesterly trend, at the eastern edge of the Tyrendarra area, passing between Koroit and Warrnambool. The results of aeromagnetic surveys indicate vulcanism or basic intrusion along the offshore extension of the ridge. However, gravity anomalies and drilling suggest that the 'Warrnambool Ridge' is primarily a basement feature, dividing the two main regional structural trends of the Otway Basin (see Pl. 7). To the west, the main trend is west-northwest, to the east it is northeast. Aeromagnetic and seismic trends appear to curve from southwest towards the west, offshore around the 'Warrnambool Ridge'.

Onshore gravity anomalies between the 'Warrnambool Ridge' and the Otway Ranges suggest two areas of thick sediments, the 'Port Campbell Gravity Depression', and the wedge-shaped Colac Gravity Trough.

The sediments in the 'Port Campbell Gravity Depression' occur in a fairly deep localized basin thinning west towards the 'Warrnambool Ridge', north towards the edge of the Basin, and east towards the Otway Range structure. They were previously considered to occur in an embayment, but subsurface structure, partly reflected at the surface near Warrnambool, suggests that the southwestern and southern sides could be faulted. The area is thought to have been a depression with restricted access to the sea, at least from Lower Cretaceous time.

The 'Colac Gravity Trough' may have been connected with the 'Port Campbell Gravity Depression', but it now wedges towards the western side of the Otway Range structure.

A prominent, elongate, positive gravity anomaly occurs southeast of the 'Colac Gravity Trough' in the Otway Range area. The shape and intensity of the gradients on its flanks indicate a horst (the 'Otway Range Horst'), plunging to the northeast (Richards, 1963).

To the northeast of the 'Otway Range Horst', two small areas of gravity minima, bounded to west, north, and east by areas of possible basement high anomaly, may be linked offshore to the south and indicate areas of deeper sediments. The western area trends northwest from the coast near Anglesea towards Geelong, perhaps swinging round, with a possible re-entrant west of the nose of the 'Otway Range Horst', to link with the 'Colac Gravity Trough'. It is separated from the eastern area by a small gravity high over the Bellarine Peninsula where Lower Cretaceous Eumeralla sediments crop out.

The eastern area shows a slightly deeper trough coincident with Port Phillip Bay. The steep gravity gradient on its eastern side is probably associated with the Selwyn Fault, forming the eastern margin of the Otway Basin.

Seismic surveys

Seismic reflection records of all marine surveys, except the Warrnambool-Princetown survey which used the Seismic Underwater Explorer (SUE) equipment, and the greater part of the land surveys were re-interpreted.

The seismic records show folds below the unconformity at the base of the Sherbrook Group and Waarre Formation (Pl. 7). The structures show predominant west-northwesterly trends particularly in the faults to the west of Warrnambool, and northeasterly trends in the eastern half of the basin. Structures near Warrnambool and in the Port Campbell area appear to be more complex. Near the margin of the present-day continental shelf, the pre-Sherbrook Group beds dip towards the coastal area.

The contour map of two-way time to the base of the Sherbrook Group and Waarre Formation (Pl. 8) shows structural lineaments similar to those in Plate 7. The isochron map (Pl. 9) shows scattered troughs of thick Sherbrook Group sediments onshore and offshore. They appear to be thickest just south of Mount Gambier in a graben which appears to extend northwest slightly offshore, and southeast to the area north of Portland. Contours on the base of the Wangerrip Group (Pl. 10), and the isochron map for the Wangerrip Group (Pl. 11), show that the thickest development is in the same area, although a shift in the axis of the trough may have occurred. Other thick deposits with well developed foreset bedding appear to occur near the edge of the present-day continental shelf; another zone of foreset bedding occurs parallel to the coastline west of Warrnambool.

The structure map of the base of the Heytesbury Group (Pl. 12) shows few structural features; the Group gradually becomes deeper offshore and thins out downslope from the edge of the continental shelf.

TECTONIC HISTORY

by R. Bryan and M.A. Reynolds

The Otway Basin includes all the areas of Cretaceous and Tertiary deposits in southeastern South Australia and southwestern Victoria.

Geophysical data show that a single broad basin developed south of the Murray Basin during the Cretaceous and Tertiary. The limits of Tertiary deposition closely match those of the Cretaceous. There is no evidence of large scale diastrophism in southeastern Australia at the end of the Cretaceous, and Tertiary sedimentation probably developed in a slightly modified version of the Cretaceous basin.

Major lineaments

The eastern margin of the basin is defined by the Selwyn Fault east of Port Phillip Bay. A line of steep magnetic gradients with a south-southwest trend extends from about 20 miles offshore from the Selwyn Fault towards the eastern side of King Island, and may be a continuation of the fault. The margin of the basin is assumed to follow this fault for about 60 miles to a prominent submarine magnetic high and then to swing southwest to the west of King Island. Faulting along the line of steep magnetic gradients is also suggested by seismic surveys (Pl. 7) which indicate several short faults with some offsetting; their age appears to be late Lower Cretaceous, perhaps extending into the Upper Cretaceous. Movement on the Selwyn Fault was Late Tertiary or Quaternary, and displacement of more than 1400 feet is suggested by Wannaeue Bore No. 13. The Selwyn Fault and other structures in the Palaeozoic rocks along Mornington Peninsula trend north-northeasterly.

Elsewhere regional structural lineaments are either meridional (see Pl. 2) - east of Ballarat and along the western side of the Grampians (Spencer-Jones, 1965) - or northwesterly as in the Black Ranges and Dundas Range. Farther west, towards the State border, the regional structures have a northwesterly orientation which is, perhaps, most evident in the Kanawinka lineament, probably a fault in the basement, which is reflected by scarps formed in the Tertiary limestone cover.

Boutakoff & Sprigg (1953) indicated that the Kanawinka Fault was a controlling factor in the development of the 'Gambier sunklands' and had a southwest throw of 2000 - 3000 feet. Sprigg (1952) postulated the existence of a 'buried escarpment of the Padthaway - Dundas Horst ... (which probably came into existence in pre-Mesozoic times ...)'. This 'horst' was regarded by Sprigg as a major northwest high separating Otway and Murray Basin sedimentation. Boutakoff (1963) re-affirms that the Kanawinka Fault is a major feature with a total throw of 3000 feet and states that it is a high-angle overthrust.

Brown (1965) thought that the Kanawinka Fault was less important than usually supposed, that the escarpment to the southeast was erosional (as shown in Pl. 2), and that the mainline of basement faulting is subsurface and offset to the east. This suggestion conforms with the gravity results which show a parallel northwest trend of steep gradient through Casterton (Pl. 7); seismic surveys, however, show that some early Tertiary faulting occurred to the southeast along the Kanawinka lineament.

Although the margin of the Otway Basin in South Australia more or less follows the limits of Tertiary deposition, the main boundary of sedimentation appears to be the fault suggested by steep gravity gradient extending southwest from north of Lucindale to north of Guichen Bay. This fault is parallel to the Cape Jaffa Fault of Grant (1954) and marks the northern edge of the 'Cape Dombey Gravity Trough'.

The regional trend shown by the Padthaway Ridge at the northwestern onshore end of the Otway Basin (and to the north of the Guichen Bay/Lucindale fault) is northwest, parallel to the Kanawinka lineament. The ridge has commonly been referred to as a 'horst'. However, no evidence of faulting has been found along its western side, and the name 'Padthaway Ridge' suggested by O'Driscoll (1960) is preferred. The main structural trends of the older Palaeozoic rocks within the feature vary from submeridional in the north and south, to northwesterly, as indicated by aeromagnetic surveys (CGG, 1965, and the Murray Basin Oil Syndicate Survey, included in O'Driscoll, 1960).

Structures immediately offshore west of the Padthaway Ridge also have submeridional trends (HEPL, 1965b): a graben-like feature extends from the offshore extension of the margin of the basin towards The Coorong. The total magnetic intensity contours suggest a westerly change in the regional trends farther west.

The southern limit of the Otway Basin is situated offshore, but it is impossible to plot the basement or the limits of Lower Cretaceous deposition because of the absence of reliable reflectors near the base of the Lower Cretaceous.

Weegar (1960b) suspected the presence of 'a meridional Palaeozoic high or highs ... between the Grampians-Mt Stavely area and the Warrnambool district'. He felt that this feature could form 'the basis of inherited topography in younger rocks or provide a locus for rejuvenation of structural movements in a later time'. The present study has certainly shown a marked thinning of both Cretaceous and Tertiary sediments in the Warrnambool area. However, this area does not appear to have been eroded for longer than the rest of the basin, and because most of the sedimentary units can be traced across the high, the Otway is considered to be a single basin.

Minor Structural and Tectonic Features

Cretaceous

The structure of the Sherbrook Group beds (mainly pre-Upper Cretaceous), from seismic records, is shown in Plate 7. Structures, thought to be folds, generally plunge towards the central axis of the basin, particularly in the offshore areas, and give the impression of a series of structural noses. The northwesterly plunges of folds at the eastern end of the basin clearly indicate the presence of a high along the eastern margin, and the section approximately thins towards King Island.

The west-northwest to northwest sets of normal faults older than the Sherbrook Group along the margins of horsts and grabens in the western half of the basin reflect the influence of downwarping and faulting associated with the initiation of the Otway Basin. In the eastern half, the predominant trends are north-northeasterly (parallel to the eastern margin and to Palaeozoic trends north of the basin) and northeasterly.

Although the west-northwest lineation extends into the eastern half, and vestiges of submeridional to northeasterly aligned structures are seen in the western half, the basin appears to be divided into two tectonic provinces along a line extending southwest from the Warrnambool Ridge.

Towards the close of the Lower Cretaceous the eastern and western portions of the basin tended to respond independently to tectonic activity. An example of this was the development of Waarre Formation sands in the east while the Eumeralla Formation was still being deposited in the west. At the end of the Lower Cretaceous a major change occurred in the west, leading to the rapid accumulation of a thick sequence of 'greywacke type' sediments - the Mount Salt Formation - derived from a quite different source from the underlying Eumeralla Formation. This change was not nearly as sudden or as pronounced in the eastern part of the basin, but a local uplift along the northern margin has been recorded by Weegar (1961b).

According to Leslie (1966) 'Throughout the history ... (of the basin) faulting has been the dominant expression of tectonics ... an important period of faulting commenced at the close of Lower Cretaceous time, and continued throughout Upper Cretaceous deposition'. Two dominant structural trends, northwest and northeast, were recognized by Leslie (op. cit.), McQueen (1961), Benedek (1960), Weegar (1960a), and others; most faulting is parallel to one or other of these trends. Leslie noted that the northeast trend is dominant in the east, and the northwest trend in the west.

Both the mechanism and the timing of the Otway Range uplift have been widely discussed. Weegar postulated a series of epeirogenic movements at the close of the Lower Cretaceous, resulting in the non-deposition of Upper Cretaceous or Tertiary in the Otway Ranges and the Casterton areas. Coulson (1939) regarded the Otway Ranges as an island in Tertiary times - at least above the present-day 900-foot level. On the other hand the Australian Tectonic Map Committee (GSA, 1962) reported that 'the Otway Ranges exhibit pre-Pliocene faulting and post-Pliocene updoming'. This view was also expressed by Hills (1946). Edwards (1962) attributed the uplift of the Otway Ranges to Cainozoic faulting and folding, and suggested that early Tertiary deposits in the area were almost wholly stripped off by erosion. He based this belief principally on the occurrence of a relatively high rank coal at Benwerrin (in the Otway Ranges), which had been determined by Cookson (1954) as Palaeocene to early Eocene. In the absence of any signs of metamorphism, Edwards concluded that a depth of burial of 'not less than 2500 feet of Tertiary sediments, and possibly as much as 3500 feet' would have been required to produce this rank of coal.

The Lower Cretaceous hills of the Casterton area were formed perhaps by faulting along the general alignment of the Kanawinka Escarpment at the close of the Lower Cretaceous.

The area of the basin was less at the start of the Upper Cretaceous than during the Lower Cretaceous (see Pls 8 to 10) but marine influence was very strong. The Warrnambool Ridge was a positive feature throughout the Cretaceous; the western downwarp initiated towards the close of the Lower Cretaceous continued to be the major area of deposition throughout the Upper Cretaceous and early Tertiary. A less pronounced downwarp developed east of the Ridge; it was probably associated with the intense faulting that caused such marked variations in the thickness of the Upper Cretaceous sequence in the Port Campbell area.

No major tectonic disturbance occurred at the close of the Mesozoic; the seas had gradually retreated in the Upper Cretaceous, and the next major transgression occurred in the middle Palaeocene.

Tertiary

Three separate transgressions have been recognized in the Tertiary, separated by unconformities which mark brief intervals of erosion; the only structural changes to the basin during these intervals were probably caused by epeirogenic adjustments.

McQueen (1961) has stated that a regional dip of 10° commonly occurs at the margins of Tertiary outcrops, and he regards this attitude as 'an initial dip imposed by the original sloping surface of the eroded Mesozoic rocks'. Woolley and Laws (1964) wrote that 'the regional structure consists of a gentle basin-wards dip'. Leslie (1966) noted that 'relatively little faulting took place during the period of Tertiary deposition'.

Sprigg (1952), Boutakoff (1963), and the Australian Tectonic Map Committee (GSA, 1962) all suggest that intermittent movement took place throughout the Tertiary. The Committee stated that 'in the south-east of the state (South Australia) movements took place along the north-west fault-lines which had been active intermittently since the Mesozoic. Localized folding of the Tertiary strata along the north-west axes occurred to the south and south-west of Mount Gambier and was accompanied by volcanic activity...'. Coulson (1939) suggested a pattern of north-south and east-west normal faults in the Tertiary of the Geelong area; Thomas (1959) also noted an east-west trend in the Tertiary deposits. However, the displacements were small.

On the other hand Reeves (1951) envisaged the possibility of earth movements in addition to the obvious epeirogenic adjustments affecting the Tertiary: 'contrary to general opinion Tertiary formations show pronounced folding in coastal areas of south-western Victoria'. Much of this folding was probably monoclinal drag associated with faulting. Boutakoff (1963) wrote that in the Portland area 'structure is expressed in vertical displacement leading to the development of pronounced high escarpments and consists essentially of monoclinal drag occasionally passing into true faulting'. This 'relay system of scarps' probably resulted from renewed movement along Mesozoic lines of weakness. The same argument can be applied to faulting along the Kanawinka lineament, where the surface expression of movement is only 5 to 30 feet.

Quaternary

The Otway Basin area has been more or less stable since the regression of the sea at the close of the Miocene, most of the subsequent movements being related to the widespread vulcanism in western Victoria and southeastern South Australia.

Sprigg (1952) wrote that the Mount Gambier area during the Quaternary was a 'crestal locus of up-warping'. The Australian Tectonic Map Committee (GSA, 1962) also referred to a broad northeast-trending regional upwarp northwest of Mount Gambier during the Quaternary, although O'Driscoll (1960) thought that it occurred from upper Eocene to Recent. The seismic contours on the base of Unit B (Pl. 12) show the same type of feature. Small displacements and minor folds are seen in outcrop, mainly in coastal scarps, but also in some of those areas not masked by volcanic deposits and unconsolidated sediments.

SEDIMENTATION

by M.A. Reynolds and R. Bryan

Pre-Jurassic

By Triassic or early Jurassic time, the Otway Basin region was a land mass perhaps bounded on the southern side by Precambrian and Lower Palaeozoic rocks extending westerly from King Island and Tasmania. Regional trends were southeasterly to meridional, following those of the Tasman Geosyncline. Northwest trends resulting from the Kanimblan Orogeny in the Carboniferous were superimposed on the region.

Drilling onshore has shown that some parts of the region are underlain by basement. Metamorphic basement has been encountered at 11,513 feet in the east (Fergusons Hill No. 1), and at 8022 and 6755 feet in the north and northwest (Casterton No. 1 and Kalangadoo No. 1 respectively). In the central area, basic volcanic rock occurred at 7874 feet (Pretty Hill No. 1).

The presence of Permian below Otway Basin sediments has been shown in western Victoria and Yalimba Bore, and both Permian and Triassic spores have been found in the Otway Basin succession. The nearest known Triassic outcrops are at Bacchus Marsh northwest of Melbourne and in the Tasmanian Basin. Such sediments may be preserved as outliers in restricted features such as glacial valleys, or grabens and half-grabens within basement.

The subsidence which led to the formation of the Otway Basin was probably Upper (or earlier) Jurassic at a time of great crustal expansion. The Basin is a graben or half-graben with prominent northwest and northeast lineaments. The oldest known sediments of the Otway Basin sequence are those of the Upper Jurassic or Lower Cretaceous Unit T.

Upper Jurassic - Lower Cretaceous

Cretaceous outcrops are recorded from the Otway Ranges and Geelong area (Barrabool Hills and Bellarine Peninsula), a small inlier on the eastern side of Port Phillip Bay, and in the Merino-Casterton area. These sediments are now thought to be mainly Lower Cretaceous - though they have previously been reported as Jurassic - and they can be equated with the Eumeralla Formation. Other Lower Cretaceous units, P-R and J-H, and the Upper Cretaceous succession in the Otway Basin have only been reported from the subsurface.

Conglomerates occur in the outcrops (Edwards & Baker, 1943; Benedek, 1960; Weegar, 1960a; Leslie, 1966; etc.). Basal conglomerates occur in the Barrabool Hills and Casterton areas near the margins of Lower Cretaceous sedimentation. The extent and significance of intraformational conglomerates is difficult to gauge because of the lack of marker horizons within the Lower Cretaceous. Weegar suggests that they are probably caused by local or even regional shoreline oscillations.

The sediments of Unit T occur in the northwest of the basin in Casterton No. 1, where they overlie metamorphic basement, and perhaps in Fergusons Hill No. 1, where a very thin sandy layer rests upon metamorphic basement. The environment in the northwestern part is thought to have been paralic with low-energy conditions initially, becoming high-energy later, perhaps because of uplift of adjacent metamorphic and granitic terrain. The presence of potash feldspar and unstable rock fragments in the sandstone indicates that mechanical weathering was predominant and transportation rapid. The rock fragments indicate a low-grade metamorphic rock and granite source similar to the Padthaway Ridge, where granite intrudes the Kanmantoo Group. The presence of volcanic detritus in the sediment suggests contemporaneous vulcanism and perhaps some form of associated diastrophism.

The absence of Unit T above Unit V (low-grade metamorphics) in Kalangadoo No. 1, refraction seismic data, and the pattern of the residual Bouguer anomaly profile suggest that Unit T was deposited in a narrow graben trending northeast near Penola in the western part of the basin.

The thin sand in Fergusons Hill No. 1 in the east could be at the outer limit of a wedge of Jurassic(?) sediments thickening to the north below the Port Campbell/Colac area. There is no equivalent to Unit T between basement and Unit R in Pretty Hill No. 1, so the Warrnambool Ridge was apparently an influence on sedimentation from the beginning.

The Geltwood Beach Formation and Unit R ('Pretty Hill sandstone') have only been recognized in wells west of the Warrnambool Ridge. The Geltwood Beach Formation is composed of Unit R sandstone interbedded with Eumeralla type mudstone, greywacke and subgreywacke.

Granite and high-grade metamorphic rocks are probably sources for Unit R. These and additional, volcanic, areas contributed to the Geltwood Beach.

The thickest Geltwood Beach sequence (in Geltwood Beach No. 1) contains about as much sandstone of Unit R type as occurs in Pretty Hill No. 1. However, the thickness elsewhere is not constant, and R-type sandstone is not so abundant in the Geltwood Beach wells to the north. The thickness variations may indicate a northwest graben with adjoining horsts, in the western part of the Basin.

The Eumeralla Formation is the thickest, most homogeneous, and laterally continuous, stratigraphic unit in the Otway Basin. Apart from some lenticular sands in the west, the bulk of the Formation is chloritic mudstone with subordinate greywacke, subgreywacke, and volcanic sandstone.

Several authors (Edwards & Baker, 1943; Weegar, 1960a; McQueen, 1961; Sprigg, 1964; and Leslie, 1966) have suggested a land mass to the south as the provenance of the bulk of the Eumeralla Formation. McQueen considered that the heterogeneous Palaeozoic rocks to the north of the Basin were also a likely source. Weegar regarded a Bass Strait land mass as the source of the Eumeralla Formation of the Otway Range, and a northern mass as the source of equivalent sediments to the west. Edwards & Baker were unable to relate the bulk of sediments to any Palaeozoic exposures to the north. They noted the close similarity in lithological composition to Triassic sediments of northeastern Tasmania - a similarity in chemical composition has been noted (Hale, in Spry & Banks, 1962) - and suggested that a Bass Strait land mass could have supplied material to the north and to the south in the Mesozoic.

Dellenbach (1965b) considered that the volcanic material was derived from contemporaneous volcanics emanating from centres within the Otway Basin, concentrated near the Bass Strait. He explained the comparative absence of flows by the rapid breakdown and removal of extruded material in the subaqueous environment.

Although the northern land mass between the Otway Basin and Murray Basin contains large areas of material which could have contributed detritus to the Eumeralla sediments, a greater variety in facies might be expected from a consistently active northern provenance. Marginal conglomerates are known along the northern edge (Edwards & Baker, 1943), but they are locally derived and limited in extent. The corrected offshore seismic

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records show general apparent dips to the north. Therefore an offshore land mass and contemporaneous vulcanism are thought to be the main sources of the Eumeralla Formation. The thin sands within the formation in the western part of the basin, which thin away from the northern margin and differ in composition from the bulk of the Formation, were probably derived from the northern land mass.

Permian and Triassic spores in the sediments indicate that Permian and Triassic sediments contributed to the formation.

Plates 3A and 3B show that, on palynological evidence, the lower part of the Eumeralla Formation in the eastern part of the basin is of the same age as Unit P-R in the west, despite the difference in sedimentation between the areas east and west of the Warrnambool Ridge at that time. The Ridge subsequently became covered by sediments of the Eumeralla Formation and uniform conditions of deposition returned to the basin. Although covered by the Eumeralla and by most subsequent units, the Warrnambool Ridge retained its influence on sedimentation until the early Tertiary.

Minor local uplifts along the northern margin may account for the formation of sandy lenses such as the 'Heathfield sand', during the later phase of Eumeralla sedimentation. Faulting and possibly folding within the basin are indicated by seismic evidence, and palynological evidence shows that much of the Eumeralla Formation may have been eroded from below the 'Heathfield sand' in areas west of Casterton No. 1.

Towards the end of the Lower Cretaceous, the pattern of sedimentation changed. The thick Waarre Formation sandstone formed to the east of the Warrnambool Ridge. Minor marine influence during early sedimentation in the west and in the Port Campbell area was followed by regression and the deposition of coarse terrigenous sands and conglomerate similar to the thin sandstone lenses in the Eumeralla Formation in the west. There is little evidence to support Weegar's (1961b) contention that the Waarre Formation is reworked 'Otway Group' derived from an uplifted area such as the Otway Ranges.

Eumeralla sedimentation with some marine influence continued into the Upper Cretaceous, west of the Warrnambool Ridge.

Tectonic activity formed the ridge along the Selwyn Fault lineament (between King Island and Mornington Peninsula), and vulcanism declined, at the end of the Lower Cretaceous and early in the Upper Cretaceous.

Upper Cretaceous

The Sherbrook Group is essentially Upper Cretaceous, although it may extend from uppermost Lower Cretaceous into the lowermost Palaeocene.

The Warrnambool Ridge (BMR, 1966) had widened, dividing the basin into an eastern province where the Flaxmans Formation and Belfast Mudstone were formed, and a western province where the Mount Salt Formation was deposited.

The Flaxmans Formation is a localized sand body, intersected in wells in the Port Campbell area and extending westwards as far as Pretty Hill No. 1, which unconformably overlies the Waarre and Eumeralla Formation and is conformably overlain by Belfast Mudstone. It is generally less than 200 feet thick, and consists of sandstone and mudstone.

Deposition of Flaxmans and the basal part of the Mount Salt Formation under near-shore high energy conditions marked the beginning of the Upper Cretaceous marine transgression. The Palaeozoic land masses to the north and the areas of uplifted Lower Cretaceous were the main source of the sediments from early Upper Cretaceous onwards.

The Belfast Mudstone is thicker and more widespread than the Flaxmans Formation, extending westwards to Eumeralla No. 1 and possibly to Heywood No. 10 Bore. It was laid down in confined and placid water.

Taylor (1964b) extends the 'Flaxmans Beds' to the north in the Port Campbell area beyond the limits of the Belfast Mudstone; and Bock & Glenie (1965) interpose the 'Nullawarre Greensand Member' between the Flaxmans Formation and Paaratte Formation in the northern area, as a landward facies of the Belfast Mudstone.

The Mount Salt Formation was deposited west of the Warrnambool Ridge in a major trough extending from southeastern South Australia to western Victoria. This trough occupies the same axial part of the basin as a Lower Cretaceous graben south of the Kalangadoo horst. The Formation ranges in thickness from 66 feet at the edge of the trough to more than 3500 feet in the centre (Mount Salt No. 1). Cycles of sedimentation from sandstone to siltstone to shale occur in the lower part of the succession, but not in the upper sandier part. The Mount Salt Formation is the time equivalent of the Waarre, Flaxmans, and Belfast Formations and is a mixture of Flaxmans and Belfast facies although it contains no volcanic rock fragments.

The apparent evidence of regression in the upper part of the Mount Salt Formation in the western half of the Otway Basin, while marine influences persisted in the Port Campbell area, is thought to be caused by rapid infilling of a subsiding graben by detritus from rising marginal areas on the north and south. As the graben filled, marine influence waned, alluvial sources became more important, and rivers supplied sand and subordinate silt from the land masses to the north. Sprigg (1964) suggests that the 'steep foresets, slumping, wedging, and rapid interplay of marine and non-marine depositional conditions' indicate a major delta derived from the ancestral River Murray drainage system. The deltaic environment probably began farther northwest than Sprigg's 'Nelson Embayment', and developed in a trough which was open to marine incursion at its southeastern end near Portland.

Regression continued during the Upper Cretaceous. The Paaratte Formation extends throughout the onshore part of the basin and probably offshore, conformably above the Belfast Mudstone in the east (although overlapping Flaxmans in part), and above the Mount Salt Formation in the west. Thicknesses range from more than 2000 feet in the Mount Salt No. 1 and Nelson Bore to less than 800 feet in most other areas. The greatest thickness appears to be west of the Warrnambool Ridge, though not as far west as that of the Mount Salt Formation.

Except for its greater sand content, the composition of the Paaratte Formation is similar to that of the Mount Salt Formation, and both reached their maximum known thickness west of the Warrnambool Ridge. A similar provenance is therefore suggested. The effects of flood-outs from the old river system became more widespread as regression continued, and the courses of the river channels meandered more widely across the region. The deposits have been termed 'marginal marine' by Taylor (1964a).

The Curdies Formation is principally a sandstone sequence with subordinate mudstone and coal (which becomes more abundant towards the top). Its thickness varies considerably, and the greatest development appears to be in the eastern part of the basin. Curdies conformably overlies the Paaratte, but its upper limit is a basin-wide unconformity.

The provenance is similar to that of the Paaratte, but in the Curdies the sand/shale ratios are higher, and reflect the more alluvial nature of the deposits. Regression is confirmed by coal deposits in the upper beds, the environment having changed from marginal marine to paludal.

Early sedimentation of the Sherbrook Group in the Upper Cretaceous appears to have been restricted to the western half of the Otway Basin and to a marine embayment in the Port Campbell area. Later sedimentation was more widespread, and the Curdies Formation, at least, is thought to extend into the Gippsland and Bass Basins. The Port Campbell and Port Phillip Bay areas may have been linked at this time by a strait which separated the Otway Ranges from the mainland during the late Upper Cretaceous.

In summary, the Upper Cretaceous was initially a period of instability; tectonic activity, mainly faulting, influenced sedimentation, particularly in the west. A northern source exerted most influence on the composition of the sediments. The environment completed a cycle of transgression and regression, changing from marine to marginal marine and non-marine, at least in the onshore part of the basin.

The unconformity which divides the Sherbrook Group and the Wangerrip Group is older than middle Palaeocene and could be late Upper Cretaceous, or early Palaeocene. It is here accepted as the break between the Mesozoic and the Cainozoic.

Palaeocene - middle Eocene

After a short hiatus in the lower Palaeocene, a marine transgression occurred which was more widespread than the early Upper Cretaceous invasion, and was followed by regression.

The full cycle of sedimentation is represented by the Wangerrip Group. The initial transgression is shown by the Pebble Point Formation, which varies in thickness from 100 feet to 300 feet.

Foresetting in the Wangerrip (Pl. 11) occurs mainly in the offshore areas beyond the continental shelf, but a prominent belt occurs onshore from Port Fairy to south of Eumeralla No. 1 in the Tyrendarra area; seismic records show the foreset beds to be low in the Wangerrip, possibly in the Pebble Point Formation.

The Dilwyn Formation is more widespread than the Pebble Point and shows the change from transgressive to regressive conditions. It is composed of sandstone and micaceous and carbonaceous siltstone and shale; the clay content decreases and the carbonaceous content increases towards the top.

Deposition was in a paralic environment. Sequences in wells show several brief marine incursions in a succession of deltaic deposits. The Warrnambool Ridge was still important and in the western half of the basin a broad deep downwarp developed, similar to that in the early Upper Cretaceous though its central axis was shorter and farther to the north. Sedimentation continued in the Port Campbell area in a much smaller basin than in the Upper Cretaceous and perhaps in depressions along the modern continental slope (beyond the 100-fathom line).

The provenance was probably to the north. Carbonaceous material was derived from an apparently well drained and well wooded terrain (Baker, 1950).

Upper Eocene - Oligocene

Near the end of Wangerrip time (early Eocene?), uplift began along the divide between the Otway and Murray Basins, and led to the deposition of the basal Tertiary sands of the Murray Basin. The earliest movements of this uplift may have been responsible for the regression in the Otway Basin at the end of the Wangerrip. Some of the movements during or after Wangerrip time, extending into the Heytesbury Group, were probably also associated with continued uplift along the divide. In the western half of the basin, trends were still predominantly northwest, but a prominent northeast fault occurs east of the Nelson Bore. West of the faulted zone, in the onshore part of the Otway Basin in south-eastern South Australia, is the northeast-trending 'Mount Gambier Upwarp' (Sprigg, 1952, see Fig. 8) believed to have been active from upper Eocene to Recent (O'Driscoll, 1960).

The trends in the eastern half of the basin were also dominantly northeast during the early Eocene.

The Heytesbury Group was deposited in two main transgressions: one in which the Nirranda Group of the Port Campbell area was formed during the upper Eocene and Oligocene; and one which began in the Oligocene and extended into the Miocene, during which units Bc and Bb were deposited.

By the end of Wangerrip time, the Otway Basin was a shelf across which sediments were transported.

The nearshore high energy facies of unit C was restricted to the west of the Warrnambool Ridge over a shelf region with local grabens; low energy conditions in deeper water prevailed in the eastern half of the Otway Basin. At least part of the island of the Otway Ranges was submerged at this time. The evidence suggests a stable shelf in the west and a slowly subsiding area to the east.

The end of unit C deposition is marked by regression in the Port Campbell area, where the unfossiliferous Point Ronald Clay was deposited, and in the Torquay area, where freshwater sediments and volcanics of the Angahook Member overlie the Demons Bluff Formation (Raggatt & Crespin, 1955). A period of erosion is indicated in the western half of the basin, where the equivalent of Bc apparently rests directly on the Pebble Point Formation in the Knights Quarry, near the southern edge of the Kalangadoo horst.

Oligocene - Miocene

A marine transgression followed deposition of unit C, and thin deposits of glauconitic marly limestone and calcarenite were formed (Unit Bc) locally in the early stages.

Unit Bb followed Bc conformably, and the transgression became the most widespread in the history of the onshore portion of the basin. The limestone and marl facies are thickest in depressions marginal to the Warrnambool Ridge and at least 1900 feet in Flaxmans No. 1. Spicular marly limestone and chert occur west, and non-cherty spicular marls east of the ridge in the lower Bb, but a polyzoal limestone facies was widely deposited in the upper Bb. The upper Bb transgression extended across the Padthaway Ridge into the Murray Basin (Hills, 1946, p.273), although the Ridge may have acted as an archipelago and partly restricted access (Ludbrook, 1961).

A sharp regression occurred at the end of Unit Bb time.

Pliocene - Recent

Unit Ab was deposited during a short post-Miocene transgression and appears to have been restricted to the western part of the basin in the Pliocene to Pleistocene. Its maximum known subsurface thickness is 210 feet, in a structure hole drilled in the Casterton area (Brown, 1965).

TABLE 12: FLUID OCCURRENCES IN SOME OF THE LITHOSTRATIGRAPHIC UNITS

WELL NAME	LITHOSTRATIGRAPHIC UNITS OF OTWAY BASIN							
	D	G	J	M	P	R	T	V
Anglesea No I				♦				
Casterton No I					◐		◐	
Eumeralla No I (A)				◐				
Fergusons Hill No I (A,B)	○		○	☀ ◊ ♦				
Flaxmans No I (A,B)		◊	◊	☀				
Geltwood Beach No I(A,B)				◊				
Heathfield No I (C)				◊				
Kalangadoo No I (B)				◐				☀
Mount Salt No I (A)		◐						
Penola No I				♦	☼			
Port Campbell No I(A,B)		☼ ◒ ◕	☀ ◐					
Port Campbell No 2 (D)			◊					
Port Campbell No 3 (E)		◊	◊	◊				
Port Campbell No 4 (B)		◕	◐	◒ ☀ ◐				
Pretty Hill No I						◐		
Sherbrook No I (A)		◐	○					
Tullich No I (B)				○ ◐	☼ ◐			

☀	*Gas*	(A)	*Water analyses in Scorer (1965)*
☼	*Trace of gas*	(B)	*Gas analyses in B.M.R. (1966, appendix I)*
◊	*Gas cut water*	(C)	*Gas: 72·00% CH_4, 0·51% C_2H_6, 0·15% higher hydrocarbons, 2·30% O_2, 0·80% CO_2, remainder N_2*
♦	*Gas cut mud*	(D)	*63–95% CH_4*
◒	*Trace of oil*	(E)	*Not subsidized: analyses not available*
◐	*Saltwater*		
◕	*Brackish water*		
○	*Fresh water*		

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RESERVOIR DATA

by J.D.T. Scorer

Although several wells have had substantial shows of gas, no commercial hydrocarbon accumulation has yet been found in the Otway Basin. Good initial flows of gas were obtained in Port Campbell No. 1 (4.2 MMcf/day from the Waarre Formation), Flaxmans No. 1 (250 Mcf/day from the Eumeralla Formation) and Port Campbell No. 4 (160 to 219 Mcf/day from the Eumeralla Formation). None of these flows was sustained, and in each case the reservoir pressure fell rapidly, indicating that the zones tested were very small.

The summary of testing which follows gives details of significant fluid recoveries, and indications of reservoir conditions for each well; details of fluid occurrences for some of the lithostratigraphic units are shown in Table 12.

Eumeralla No. 1

Two tests in the Eumeralla Formation recovered small quantities of mud and salt water (average salinity 10,000 ppm chlorides). Strong solvent fluorescence was noted in cores containing coal fragments and carbonaceous shale partings; and gas detector readings, presumably from coal gas, were obtained during drilling. Core samples from the Eumeralla Formation had permeabilities ranging from 3 md to nil. Eumeralla No. 1 was drilled on the downthrown side of a prominent subsurface fault.

Fergusons Hill No. 1

The Waarre Formation produced fresh water; a slight gas flow and gas-cut mud were recovered from the Eumeralla. This well was drilled to test pinchout possibilities against a subsurface structure.

Flaxmans No. 1

Flaxmans No. 1 was drilled on a closed seismic structure, part of an extensive line of folds (see Pl. 7). The area is extensively faulted.

Gas-cut water was produced from the Paaratte Formation, which had some intervals of good porosity and moderate permeability. The Waarre Formation was porous and permeable, although it appeared more argillaceous than in the Port Campbell area. This formation produced salt water with small quantities of gas. The only indication of oil is some staining in cuttings from 10,928 feet and in core 43 (11,225-11,235 ft).

Core analyses of the Eumeralla Formation all showed nil permeability and the production of gas was thought to come from fractures. The initial flow-rate was 250 Mcf/day with some condensate, but in an extended flow period the rate dropped to zero.

Geltwood Beach No. 1

Signs of hydrocarbons in this well were negligible, apart from a small amount of gas in one test in the Eumeralla Formation. Total dissolved solids in Eumeralla waters ranged from 20,000 to 28,000 ppm. Core samples showed permeabilities up to 212 md above 5000 feet; below this depth the maximum permeability was 8 md. The Geltwood Beach structure is a small fold, with little closure, perhaps associated with transverse faulting in basement.

Heathfield No. 1

A test interval 4078-4144 feet in the Eumeralla Formation produced a strong flow of gassy salt water (total solids 26,840 ppm). Coaly material is common in core samples below 2879 feet, which exhibited solvent fluorescence. The well tested a seismic structure southwest of the Kanawinka lineament, in an area of complex faulting.

Mount Salt No. 1

Thick sections in this well showed very good porosity and permeability on the Microlog. A test of the Mount Salt Formation gave a strong flow of salt water. Bituminous coal occurs as small amounts of brownish black organic material in the Curdies Formation (Dellenbach, 1964). The Mount Salt structure was located photogeologically and confirmed by structure drilling; it may be associated with transverse faulting in basement.

Port Campbell No. 1

The Waarre Formation is very permeable, and initially produced gas at a rate of 4.2 MMcf/day. The well then started to produce salt water, and attempts to shut this off were unsuccessful. Formation pressure dropped rapidly, which suggests that production came from a small lenticular sand. The target was a structure delineated by seismic surveys. Waxy oil was recorded from core 17 at 4757 feet in the Paaratte Formation (FBH, 1960a).

Port Campbell No. 2

The Waarre Formation produced gas-cut mud and gas-cut salt water from a sand of only moderate porosity and permeability. Port Campbell No. 2 is in a structural environment similar to No. 1, but is between two faults downthrowing east, and was located to drill increased section.

Port Campbell No. 3

Although core porosities and permeabilities from the Waarre Formation were very good, the intervals tested gave only small flows of gas and salt water. A small gas flow was obtained from the Paaratte Formation; the Eumeralla Formation produced a small flow of gas and salt water. This well appears to have been drilled on an anticline.

Port Campbell No. 4

The Waarre Formation had good porosity and permeability but produced salt water on test. An initial gas flow of up to 219 Mcf/day, with small quantities of oil emulsion, was obtained from the Eumeralla. Pressure declined sharply with flow. The seismic structure drilled was a small anticline.

Pretty Hill No. 1

A well developed sandstone at the base of the Eumeralla Formation produced a strong flow of salt water. No indications of hydrocarbons were obtained. Pretty Hill No. 1 was on a small seismic structure north of a prominent fault which downthrows to the south.

Sherbrook No. 1

Permeability in the Waarre and Eumeralla Formations was fair. Fresh water was produced from the Waarre. The well was located to test pinchout possibilities against a subsurface structure.

Tullich No. 1

Core analysis and the Microlog indicated that porosity and permeability were low over most of the Eumeralla Formation. Fresh to brackish water was produced from the top of the section, and gassy salt water from the bottom part. Gassy water was also obtained from the underlying Geltwood Beach Formation. Tullich No. 1 is located in a somewhat similar structural environment to Heathfield No. 1, and is near the extension of the Kanawinka lineament.

Reservoir prospects

Many of the hydrocarbon occurrences found so far come from small reservoirs, as shown by decline of pressure following a small amount of production; even the Waarre Formation, which is considered to be one of the best prospects, showed this tendency. The formations which may contain permeable beds and form hydrocarbon reservoirs are summarized below.

The oldest prospective zone is within the unnamed Unit T, which has good sands over the top 450 feet; it is only known from Casterton No. 1 in the west, although a thin sand above basement in Fergusons Hill No. 1 might be equivalent.

The 'Pretty Hill sandstone' (Unit R) has high porosity and permeability (up to 2756 md) throughout but occurs only in Pretty Hill No. 1. The Geltwood Beach Formation, a lithofacies variant of the 'Pretty Hill sandstone' in the western half of the Basin, contains sands with generally little or no porosity or permeability.

The exceptional thickness of the Eumeralla Formation, thought to be up to 9000 feet in the deepest part of the Basin, makes any general comment on reservoir properties very difficult. In several places in the west, Eumeralla sediments have good permeability; logs, core analysis, and drillstem testing indicate that there are very few well developed and permeable sands in the east. An initial flow of 250 Mcf/day from the Eumeralla in Flaxmans No. 1 is thought to have come from fractures.

Permeabilities up to 4840 md have been measured in the Waarre Formation, which so far has been found only in the Port Campbell area. Thicknesses have ranged from 202 to 468 feet, so that this formation must be considered to have good reservoir prospects. The potential productivity is evidenced by the results of Port Campbell No. 1, in which an initial gas flow-rate of 4.2 MMcf/day was obtained. However, the zone under test appeared to be a small lenticular reservoir. Lithological studies of the Waarre Formation indicate that part of it was deposited in fresh water and part in salt. Formation waters produced on test also include both fresh and salt. The fresh formation waters produced in Fergusons Hill No. 1 and Sherbrook No. 1 could conceivably be connate, but the high proportions of bicarbonate suggest that a meteoric origin is more likely. If this is so, then at least parts of the reservoir must be continuous over considerable distances.

In the Port Campbell area, neither the Flaxmans Formation nor the Belfast Mudstone has any good porosity or permeability. Their correlative in the western part of the basin, the Mount Salt Formation, contains porous and permeable (up to 955 md) sandstone beds.

Good porous and permeable sands are known from wells throughout the Otway Basin in both the Paaratte and Curdies Formation. Permeabilities up to 2390 md are recorded in the Paaratte Formation (Mount Salt No. 1), and 3100 md in the Curdies Formation (Port Campbell No. 4).

The basal Tertiary Wangerrip Group (Unit D) has reservoir prospects in parts of the Pebble Point Formation (good sands in Mount Salt No. 1 and Flaxmans No. 1), and Dilwyn Formation (well developed sands in all the wells examined except Kalangadoo No. 1 and Port Campbell No. 4). Younger Tertiary sediments contain widespread porous and permeable beds of sand, marl, limestone, and biocalcarenite, which crop out over wide areas and do not occur in conditions suitable for entrapment of hydrocarbons.

Summary

The most interesting examples of porosity and permeability are:

(i) The Dilwyn Formation (Unit Db) is permeable in all wells examined;

(ii) The Waarre Formation (J), which only occurs in the Port Campbell area, is permeable in each well examined;

(iii) Unit R ('Pretty Hill sandstone') only occurs in one well but is an exceptionally thick and permeable sand;

(iv) Almost continuous sands are present in Mount Salt No. 1 from 590 to 10,044 feet (T.D.);

(v) Flaxmans No. 1 has considerable sections of good sand from 2000 to 7100 feet.

Reservoir Pressures

Details of the results of drillstem tests in which a value for the static formation pressure was either measured directly or calculated from a build-up analysis show that, after allowance for possible errors, most of the pressures are close to normal hydrostatic.

The presence of what appear to be fresh meteoric waters in Sherbrook No. 1 and Fergusons Hill No. 1 suggests that parts of the formation have been flushed. There are not enough reliable pressure readings in this formation to draw any valid conclusions regarding the existence of hydrodynamic gradients. The abnormally low potentiometric levels in Port Campbell No. 1 (-515 and -497 feet) may be a result of faulting, or may simply be incorrect values. The level measured in Port Campbell No. 2 was +428 feet, representing a difference in head of 934 feet between these wells.

The expected direction of any hydrodynamic gradients is approximately southerly from elevated areas inland. The beds dip gently in the same general direction.

PETROLEUM PROSPECTS

The initial aim when undertaking this review of the Otway Basin was to stimulate interest in oil search in the region. During the course of the review, however, commercial gas deposits were discovered in the Gippsland Basin, an adjoining Basin with a somewhat similar geological history. Interest, therefore, has already been stimulated, and the following notes are designed to point out the prospects of finding hydrocarbons, and possible difficulties that might be experienced in the search.

Although the discussion is based mainly on the results of onshore exploration, the possibilities of hydrocarbon accumulations both in the onshore and offshore regions are considered. The offshore data available for study during this review were from regional aeromagnetic coverage and marine seismic surveys; no offshore drilling had been done at the time of the review. However, the ideas developed from the onshore study have been extended to the offshore region by using the geophysical data.

Hydrocarbon Occurrences

Apart from the small quantities of oil recovered from Port Campbell No. 4, only non-commercial quantities of gas have been discovered.

In the Port Campbell area, gas, mainly from the Eumeralla and Waarre Formations, generally has up to 20% and more of ethane and higher hydrocarbons. In the western half of the basin, the Waarre Formation is absent but the Eumeralla yields some gas, mainly methane (with a maximum of 3% of higher hydrocarbons). Boutakoff (1951) refers to the occurrence of hot water and inflammable gas (63% hydrogen, 20% methane, 13.5% nitrogen and traces of other gases) in the Geelong Oil Flow Well in the Torquay area (in sediments equivalent to Eumeralla Formation).

The percentage of carbon dioxide, in analyses of gas from Port Campbell Wells 1 and 2, is relatively high (5 to 23%). Unit V (fractured basement) in Kalangadoo No. 1 yielded gas which contains 80 or even up to 96% carbon dioxide. The carbon dioxide may be related to the oxidation of hydrocarbons during local volcanic intrusions. A similar explanation could be made for the escaping carbon dioxide gas at Clifton Springs (Coulson, 1933) along the Bellarine Peninsula, an area underlain by the Eumeralla Formation which has been intruded by the 'Older (Oligocene) Volcanics'. The seepage is probably along faults in that area. In yet another area affected by vulcanism, Sprigg (1961) refers to a 'big flow' of carbon dioxide gas from Yangery No. 1 Bore at Koroit.

Other units which contain small gas accumulations are Geltwood Beach Formation and Paaratte Formation. In Tullich No. 1 the Geltwood Beach Formation flowed salt water containing dissolved gas which was unusually high in nitrogen (32-62%). Gas from the Eumeralla Formation in the same well also contains nitrogen, possibly up to 18 1/2%. The only other well to record more than 10% of nitrogen is Fergusons Hill No. 1 in gas from the Eumeralla (12%). A trace of gas of unknown composition is also recorded from the Geltwood Beach Formation in a core from Penola No. 1.

The Paaratte Formation contains mainly methane in the gas show from Flaxmans No. 1. Drilling records of the Nelson Bore also refer to a 'fair show of gas' (derived from the Paaratte level) in the mud ditch.

A trace of gas and some residual crude oil in cores were recorded from the Mount Salt Formation and cores from the Dilwyn Formation showed fluorescence of unknown origin in Mount Salt No. 1.

Reports of hydrocarbons in some of the early wells drilled for oil, particularly, in southeastern South Australia, have been mostly discredited for various reasons (Gray & Croll, 1938). However, the significance of hydrocarbons in the well drilled on Knights Dome was never successfully explained (Woolnough, 1933) and it is unfortunate that drilling was abandoned before the well had been properly tested.

Offshore seepages have been suggested for the numerous strandings of dominantly asphaltic material along the shores of South Australia and western Victoria. Many reports have been made of these strandings (Wade, 1915) and other onshore seepages (Pritchard, 1924). Most of these have been referred to by Sprigg (1952 to 1964), who supports older suggestions of offshore seepages for the strandings; 'plankton bloom' was suggested for their origin by Ludbrook (1961). Analyses of the material are given in Sprigg & Woolley (1963b). Woolley & Laws (1964) suggest 'pitch dome' diapirism for the offshore seepages.

The importance of faulting throughout the history of the basin, and the evidence of tensional stresses at various times, suggest that hydrocarbon seepages may be from faults in the offshore areas.

A report of an onshore oil seepage in the Haines Landing area, about 15 miles upstream along the Glenelg River from the Nelson Bore, was never fully substantiated (Boutakoff, 1951).

Reservoir Potential of the Sediments

Unit T

The sediments are mudstone and sandstone with porous sand bodies in the uppermost 450 feet; they are thought to have been deposited in a paralic to alluvial environment. Fracture porosity may be present in parts of the unit. Unit T has been found only in the northwestern part of the basin, but a similar development may occur in the eastern half.

Geltwood Beach Formation and Unit R

Good sands with high porosity and permeability occur in the 'Pretty Hill sandstone' (Unit R), but diagenetic cementation has diminished the reservoir potential of sandy intervals in the Geltwood Beach Formation. However, in Casterton No. 1, that formation contains some conglomerate horizons and is more sandy towards the base; the change is reflected in the electric logs, which indicate some porosity. This suggests that improved reservoir conditions can be expected towards the margins of the basin. Fractures have been noted from cores.

Eumeralla Formation

Mudstone, with minor coal lenses in parts of the basin, and subordinate greywacke to volcanic sandstone form the bulk of the Eumeralla Formation. The thickness may exceed 9000 feet. Thin sandy wedges, from 20 to 120 feet thick, are known from the northwestern part. Porosity and permeability are generally low for the wells studied, although the sand/shale ratio ranges from 0.2:1 to 1.4:1. Fracturing is most prominent in Fergusons Hill No. 1 and Anglesea No. 1 (wells adjacent to the Otway Range structure).

The known hydrocarbon occurrences in the Eumeralla Formation do not appear to be restricted to any particular level: the main gas flow from Flaxmans No. 1 came from 4000 feet below the top of the unit, probably from a fractured zone.

Waarre Formation

The Waarre formation is between 200 and 550 feet thick and the sand/shale ratio ranges from 1:1 to 6:1. The sands are porous and permeable in the Port Campbell area. The formation may extend into the eastern part of the basin to a possible equivalent 105 feet thick in Anglesea No. 1.

Sherbrook Group

The tight sandstone and sandy mudstone of Flaxmans Formation and dark glauconitic mudstone of the Belfast Mudstone in the east, which are more than 2000 feet thick, are represented in the west by the Mount Salt Formation of interbedded sandstone and siltstone. The thickness ranges from 66 feet to more than 3500 feet, and the sand/shale ratio from 4:1 to 1:1. The sands show some porosity and good to fair permeability depending on the distribution of silt and cement. Their thickness exceeds 3000 feet in the west, and may reach 2000 feet in the eastern part of the basin. Sand/shale ratios range from 0.3:1 to 7.7:1. The only unit known to continue east of the Port Campbell area is the Curdies Formation.

Wangerrip Group

The Pebble Point Formation at the base is a pebbly pelletal and oolitic sandstone, 50 to 400 feet thick. A belt of foreset sands is predicted from seismic evidence to occur underneath the coastal area west of Port Fairy, adjacent to an area of calcarenite rich in ooliths (Eumeralla No. 1), and another more extensive belt of foreset sands is thought to occur along the edge of the continental shelf. The unit contains thick porous and permeable sands over most of the basin, and is more than 2800 feet thick in Heywood No. 1 Bore.

Heytesbury Group

Unit C consists of limonitic sandstone and conglomerate overlain in the eastern half of the basin by a glauconitic and limonitic marl. It is overlain by Unit Bc, which crops out over wide areas and is generally porous, so that there would be little possibility of hydrocarbons being trapped.

In the eastern half of the basin the sandy horizon at the base of C, ranging from 20 to 150 feet thick, is conformably overlain by marine marl in the Port Campbell area. The marl may not be important onshore, but an offshore extension could form a cap to some of the older more permeable units.

Petroleum Traps

The majority of deep wells drilled in the search for oil since 1959 have been sited on closed anticlines or fault traps defined by seismic exploration, although Fergusons Hill No. 1 and Sherbrook No. 1 were sited to test possible pinch-out of sediments against an uplift. Anglesea No. 1 was an off-structure stratigraphic well.

The most prominent structural features in the Otway Basin are horsts and grabens or half-grabens produced by tension, and transcurrent faults and short en echelon fractures produced by shear. Although many of the faults are post-depositional, some were contemporaneous with sedimentation, as may be expected in such a basin, which has a history of rapid clastic sedimentation, particularly in the western half, in the Upper Cretaceous and Lower Tertiary.

Fault traps or pinch-outs which have formed as a result of 'down-to-basin' faulting are to be expected. Stratigraphic traps may occur in areas of rapid clastic sedimentation where floods of coarse detritus produce localized or blanket-type sand lenses.

Folds are more common in the eastern half of the basin than in the west, as shown in Plate 7. The nature of many of the folds is difficult to determine because of inadequate seismic control, particularly offshore, but some are probably compressional. Some of the subsurface features are confined to sediments older than the Sherbrook Group, others persist into the Sherbrook and Wangerrip Groups, and the most persistent affect the Heytesbury Group. Some of the anticlinal structures appear to plunge towards the long axis of the basin. Elongated folds may show closure at one or more places along their axes; the extensive feature through Flaxmans No. 1 is typical. Some of the folds seen in outcrop in southeastern South Australia have been attributed by Sprigg (1962a) to basement shearing at depth; these are small en echelon folds with low dips on the limbs.

Anticlines or monoclines may be associated with 'down-to-basin' faulting at the edges of troughs.

Seismic records show dome-like structures in certain younger sediments, in the areas where vulcanism is known; they are perhaps caused by basaltic intrusion or extrusion. Traps could be created by updoming by the intrusions, or by draping over rises caused by the intrusions and extrusions. The latter might be expected in earlier sediments associated with the Upper Jurassic to Lower Cretaceous (?) vulcanism, or in the eastern part of the basin where the 'Older (Oligocene) Volcanics' occur.

Traps may occur below angular unconformities around the southern and eastern margins of the basin. However, throughout much of the Otway Basin sequence, most unconformities are followed by marine transgressions and the deposition of coarse-grained generally porous sediments which would not provide a seal. Traps could be developed offshore along the edges of shallow basement features such as the Warrnambool Ridge and south of Cape Otway.

The large foreset structures shown in seismic records in the area west of Warrnambool and offshore (Pl. 11) if developed in sand could supply excellent reservoirs.

Conclusions

In spite of the difficulties associated with exploration in the Otway Basin, many prospects remain to be tested both onshore and offshore.

In the western half, Unit T, the Otway Group, and the Sherbrook Group offer the best prospects. Reservoirs could be provided also by foreset beds in the Wangerrip. Structures are mainly northwest tensional and shear faults with subordinate associated small folds. Some doming may be caused by Upper Jurassic to Lower Cretaceous basic intrusions in the Beachport area, and by the 'Newer Volcanics' elsewhere. Late Cainozoic upwarp, and possible associated down-faulting, have affected southeastern South Australia and southwestern Victoria, and produced some northeast-trending structures.

Areas of interest lie along the northern margin, onshore and offshore, and along the flanks of the various grabens. Also, because the marine influence in the Sherbrook Group appears to be important southeast of the deltaic deposits of Mount Salt, the graben near Portland, apparently opening offshore to the east, might be one of the most favourable areas for the formation and accumulation of hydrocarbons.

In the eastern part of the Otway Basin, all units to the top of C in the Port Campbell area, and other areas overlain by the marl at the top of C, may be regarded as possibly prospective for hydrocarbons. However, the Upper Cretaceous section thins east of the Port Campbell area.

Good fracture porosity may occur in faulted areas; and pinch-outs appear to offer some prospects along some of the basement features such as the Warrnambool Ridge, and the edge of the shelf thought to extend southwest from Cape Otway. The marginal belt north of the Port Campbell area, extending eastwards from Lake Corangamite, offers reservoir prospects if sands similar to Unit T are present. If permeable sands exist here or farther east in the Port Phillip Bay area, the possibility of the existence of suitable reservoirs for gas storage, as well as the hydrocarbon prospects, could be considered an added incentive for exploration.

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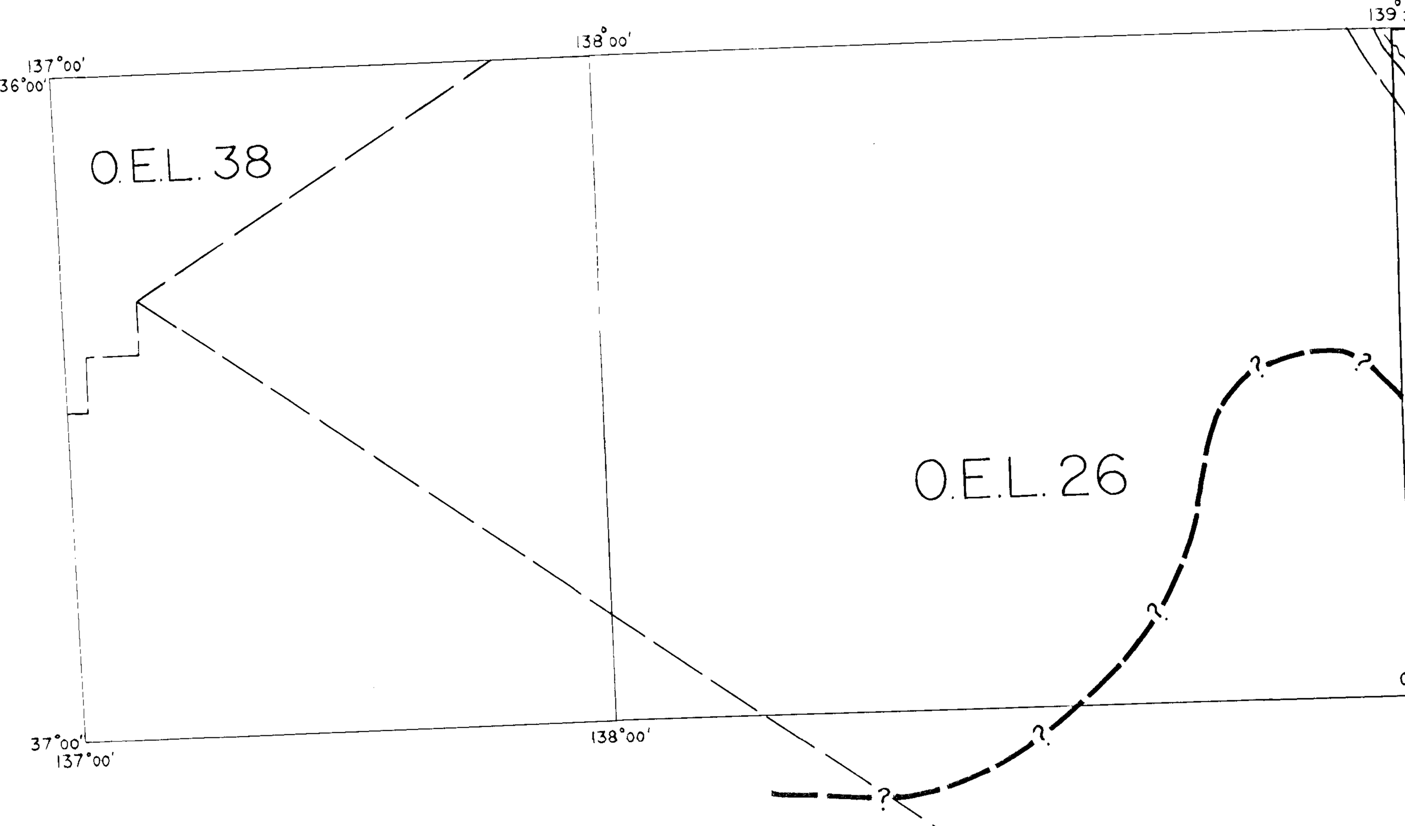
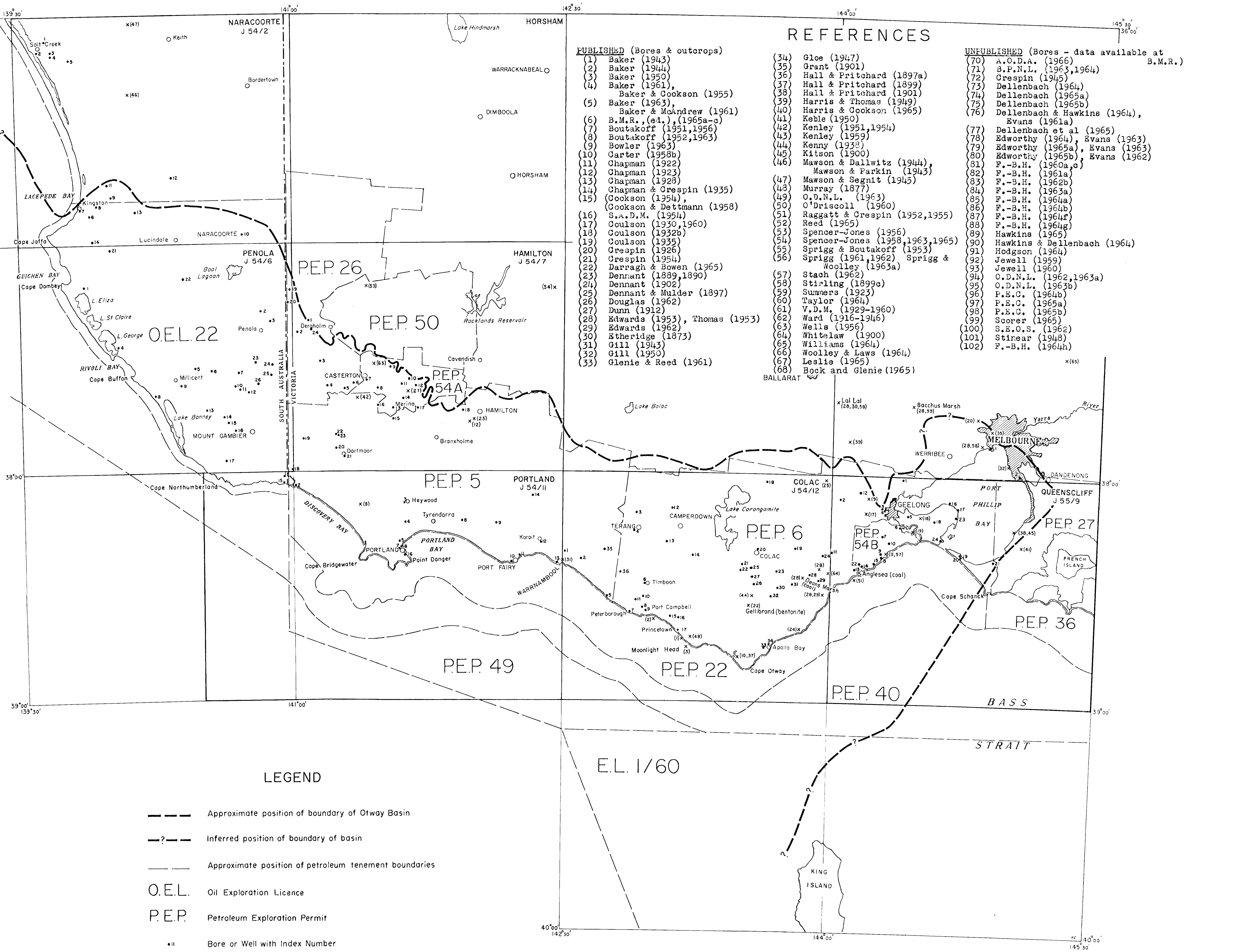
PLATE I

OTWAY BASIN LOCATION MAP





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BORE AND WELL INDEX

SOUTH AUSTRALIA

NARACOORTE SHEET (J54/2)

1. Salt Creek
2. Santo 1
3. Alfred Flat
4. Salt Creek 1
5. Salt Creek 2
6. Coorong 1 (Lacepede 42)*
7. Coorong 2 (Lacepede 507)*
8. Enterprise Oil (Lacepede 442 NE)*
9. Blackford (Murrabinna 10B)*
10. Naracoorte (Government Bore)
11. (Murrabinna 23)*
12. (Woolumbool 40)*
13. (Minecrow 106)*
14. (Bowaka 95)*

PENOLA SHEET (J54/6)

1. Robe No. 1 (15)
2. S.E. Drainage Works Bore
3. Penola No. 1 (49)
4. Beachport No. 1 (100)
5. Mount Burr (72)
6. Mount McIntyre
7. Kalangadoo No. 1 (70)
8. Geltwood Beach No. 1 (6,66,71,74)
9. Cheese Factory No. 1
10. Dismal Swamp 2
11. Dismal Swamp 1
12. Dismal Swamp 3
13. Tantanoola (S.A. Oil Wells)
14. (Springs (56,62,101)
(Mount Gambier (Producers' Oil Well)
15. Mount Gambier (A.O.C.) No. 1
16. Knights Dome No. 2 (62)
17. Mount Salt No. 1 (6,73,94)
18. Palpara No. 1
19. Comaum No. 1 (56)
20. Comaum Coal Bore (No. 1A or 2)(15,16,40)
21. (Bowaka 167)*
22. (Joyce 395) *
23. (Nangwarry 143)*
24. (Nangwarry 130)*
25. (Nangwarry 113)*
26. Tarpeena (56)

* Refers to Hundred & Section in (Reference 50)

VICTORIA

HAMILTON SHEET (J54/7)

1. Kanawinka No. 1
2. Kanawinka No. 6
3. Tullich No. 1 (77,97)
4. Heathfield No. 1 (89,91,96)
5. Bahgallah No. 2
6. Casterton No. 1 (Planet)(98)
7. Casterton No. 1 (Water Bore)
8. Sandford
9. Carapock No. 2
10. Muntham No. 1
11. Muntham No. 2
12. Coleraine
13. Merino No. 2 (27)
14. Merino No. 3
15. Merino No. 5
16. Mocamboro No. 1
17. Tahara No. 1
18. Yulecart No. 1
19. Mumbannar No. 1
20. Dartmoor No. 1
21. Dartmoor No. 14
22. Dartmoor No. 19
23. Dartmoor No. 20
24. Dergholm No. 1 (15)

PORTLAND SHEET (J54/11)

1. Caroline Nos. 2,3,4 (S.A. Oil Wells)
2. Nelson No. 1 (Glenelg No.1)(4,8,21,90)
3. Heywood No. 10 (52)
4. Bolwarra No. 1 (8,33)
5. Borthwicks (Portland North) (8,33)
6. Portland No. 2 (8,33)
7. Portland No. 3 (8,33)
8. Eumeralla No. 1 (79,84)
9. Pretty Hill No. 1 (78,83)
10. Belfast No. 4 (43,92,102)
11. Glaxco
12. Yangery No. 1 (102)
13. Wangoom No. 6 (102)
14. Kangertong No. 5 (102)
15. Caroline No. 1 (S.A. Oil Wells)
16. Portland No. 1 (33)

COLAC SHEET (J54/12)

1. Wangoom No. 2 (102)
2. Mepunga No. 2
3. Glenormiston No. 2
4. Terang No. 1
5. Flaxmans No. 1 (5,6,80,82)
6. Timboon No. 5 (93)
7. Narrawaturk No. 2
8. Port Campbell No. 1 (5,76,81)
9. Port Campbell No. 2 (5,76,81)
10. Port Campbell No. 4 (88)
11. Port Campbell No. 3 (5)
12. Koort-Koort-Nong No. 2
13. Tandarook No. 1
14. Carpendeit No. 1
15. Sherbrook No. 1 (86)
16. Fergusons Hill No. 1 (87)
17. Latrobe Bore (85)
18. Cressy No. 1
19. Birregurra No. 1 (15)
20. Colac No. 1
21. Colac No. 2
22. Colac No. 3
23. Yeo No. 5
24. Yan Yan Gurt
25. Barongarook No. 1
26. Barongarook No. 2
27. Kawarren Nos. 1-7
28. Bambra No. 1
29. Boonah No. 1
30. Gerangamete No. 3
31. Murroon No. 5
32. Yaugher No. 1
33. Krambruk No. 1
34. Krambruk No. 3
35. Panmure No. 2 (102)
36. Nullawarre No. 3 (68)

MELBOURNE SHEET (J55/5)

1. Newport (36)(58)
2. Mentone (36)

QUEENSCLIFF SHEET (J55/9)

1. Woornyalook No. 1
2. Derog No. 1
3. Barrabool No. 30
4. Gherineghap No. 1
5. Moolap No. 1
6. Connewarre
7. Duneed No. 2
8. Jan Juc No. 1-4 (51)
9. Jan Juc No. 5
10. Geelong Flow Oil (57)
11. Wensleydale No. 1
12. Wabdallah No. 1 (Bannockburn)
13. West Mineral Corp.
14. Anglesea No. 1 (75,95)
15. Point Addis Bores (51)
16. Portarlington No. 1
17. Paywit No. 3
18. Bellarine No. 1
19. Sorrento (13)
20. Nepean No. 29
21. Wannaeue No. 13
22. Angahook No. 23 (57)
23. Paywit No. 2
24. Queenscliff No. 7

Bores generally -
References (7), (9), (14), (26), (34), (50), (55), (56), (60), (61), (62), (67), (99), (101)

LEGEND

Approximate position of boundary of Otway Basin

Inferred position of boundary of basin

Approximate position of petroleum tenement boundaries

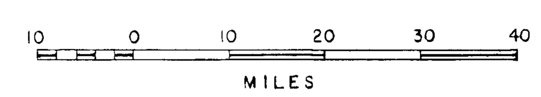
O.E.L. Oil Exploration Licence

P.E.P. Petroleum Exploration Permit

Bore or Well with Index Number

(3) Reference Number (used in Bore & Well Index)

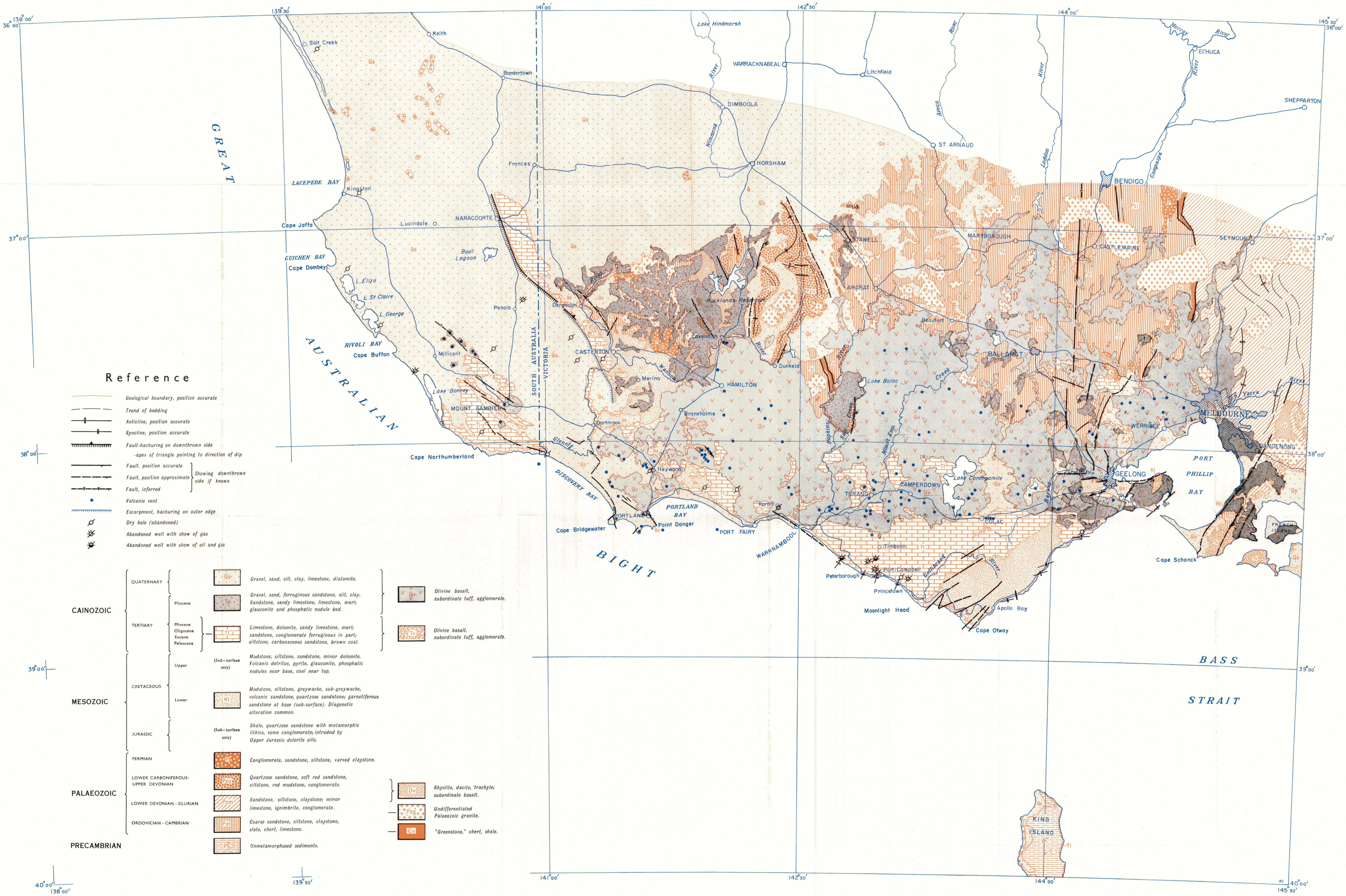
x(5) Outcrop or regional geological description with Reference Number



GEOLOGICAL MAP

OTWAY BASIN AND ADJACENT AREAS

VICTORIA AND SOUTH AUSTRALIA



Geology based mainly on the map of Sprigg (1952) for South Australia and the Geological Map of Victoria issued by the Geological Survey of Victoria in 1964

Bureau of Mineral Resources, Geology and Geophysics. August 1966

Scale 1 : 1,000,000

10 0 10 20 30 40

MILES

X-AUS-1-29

H.Z.

AGE		PALYNOLOGICAL UNIT	STRATIGRAPHIC UNITS: FORMATION NAME	SYMBOL
TERTIARY	Pleistocene			Ab
	Pliocene			
	Miocene			Bb / Bc
	Oligocene			C
	Eocene	Dk	Dilwyn	Db
	Palaeocene		Pebble Point	Dd
CRETACEOUS		Dp	Curdies	Gb
	Senonian	Xa	Paaratte	Gd
		Na	Belfast Mudstone } Mount Salt	Gf / Gg
	Turonian	Dc	Flaxmans	Gh
	Cenomanian	Ap	Waarre	J / H
	Albian	K_2b		
		K_2a		
	Aptian	Kld	Eumeralla	M
		Klc		
		Klb		
	Neocomian	Kla	Geltwood Beach — Pretty Hill	P / R
CRETACEOUS — JURASSIC				T
PALAEOZOIC			Basement	

STRATIGRAPHIC AND PALYNOLOGICAL CORRELATIONS OF OTWAY BASIN - COASTAL SECTION

WELLS LEVELLED TO BASE OF TERTIARY

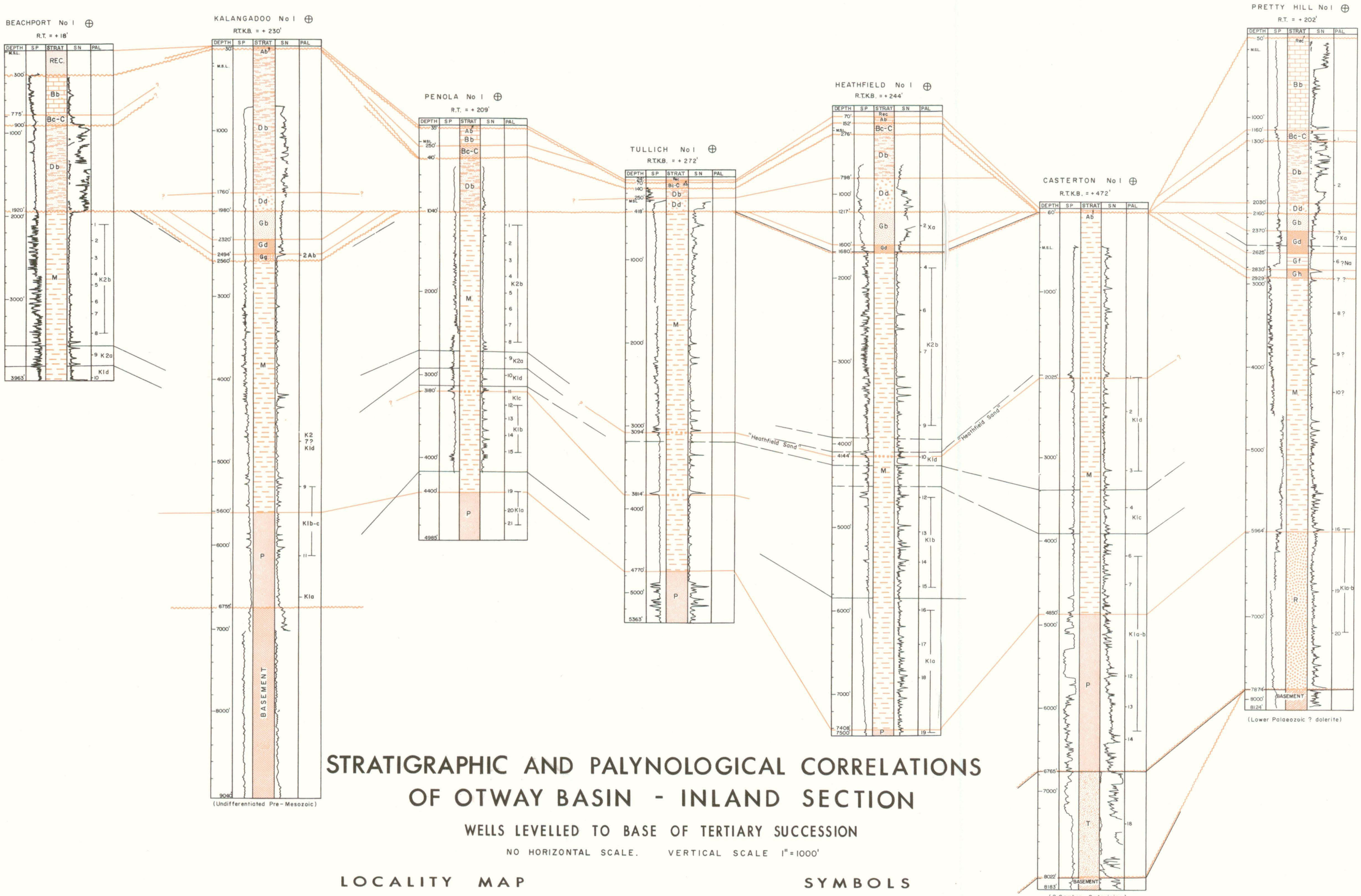
NO HORIZONTAL SCALE. VERTICAL SCALE : 1" = 1000'

SYMBOLS

- ⊕ *Well interpretation based on study of samples, E - logs and literature*
- ⊖ *Well interpretation based on study of E - logs and literature*
- ⦶ *Well interpretation based on study of literature*
- 2 *Core numbers important for palynological correlation*
- 17 *Represents core from deviated hole in Port Campbell No 2*
- JB *Junk basket core in Port Campbell No 1*
- *Unconformity*
- ? *Unconformity inferred*
- *Stratigraphic boundary established*
- ? *Stratigraphic boundary inferred*
- *Palynological boundary interpolated*
- *Palynological boundary inferred*
- SP *Spontaneous potential log*
- SN *Sonic log*
- PAL *Palynology*

LOCALITY MAP

S.A.
VICTORIA
Lacepede Bay
Discovery Bay
Portland Bay
Port Phillip Bay
Cape Otway
Scale 1: 2,534,400

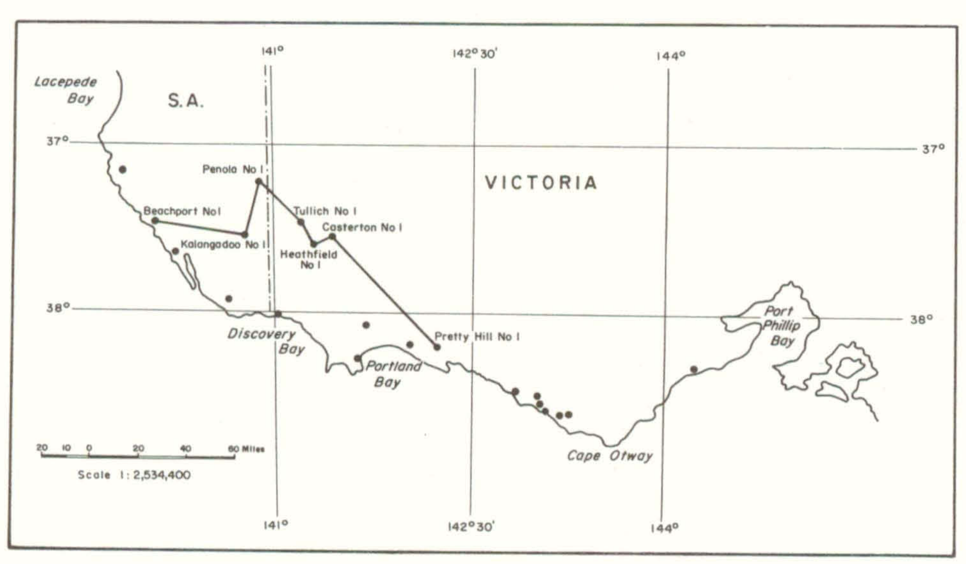


STRATIGRAPHIC AND PALYNOLOGICAL CORRELATIONS OF OTWAY BASIN - INLAND SECTION

WELLS LEVELLED TO BASE OF TERTIARY SUCCESSION

NO HORIZONTAL SCALE. VERTICAL SCALE 1" = 1000'

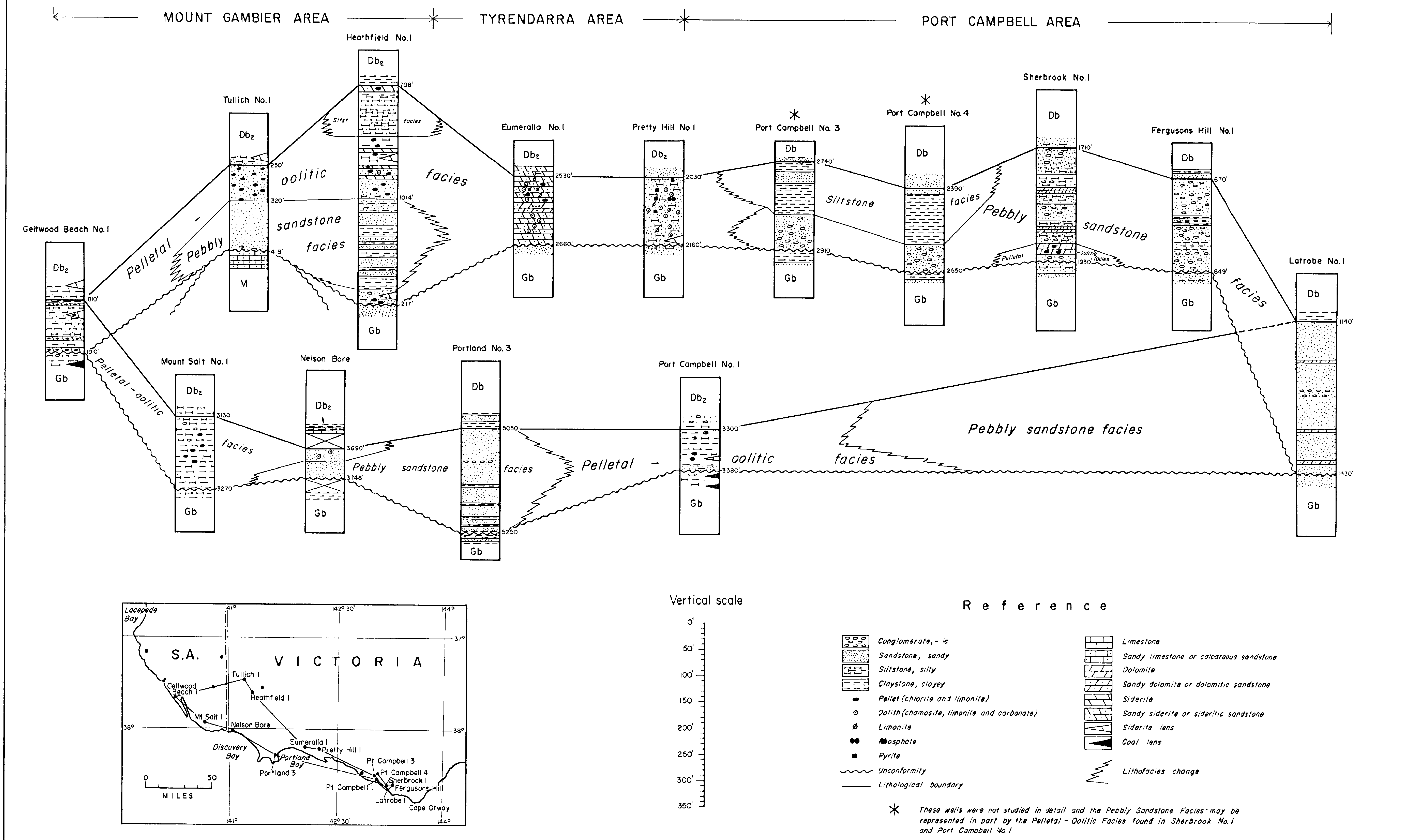
LOCALITY MAP



SYMBOLS

- ⊕ Interpretation based on study of samples, E-logs and literature
- ⊖ Interpretation based on study of E-logs and literature
- ⦶ Interpretation based on study of literature
- 12 Core numbers important for palynological correlation
- Unconformity
- Unconformity inferred
- Stratigraphic boundary established
- Stratigraphic boundary inferred
- Palynological boundary interpolated
- Palynological boundary inferred

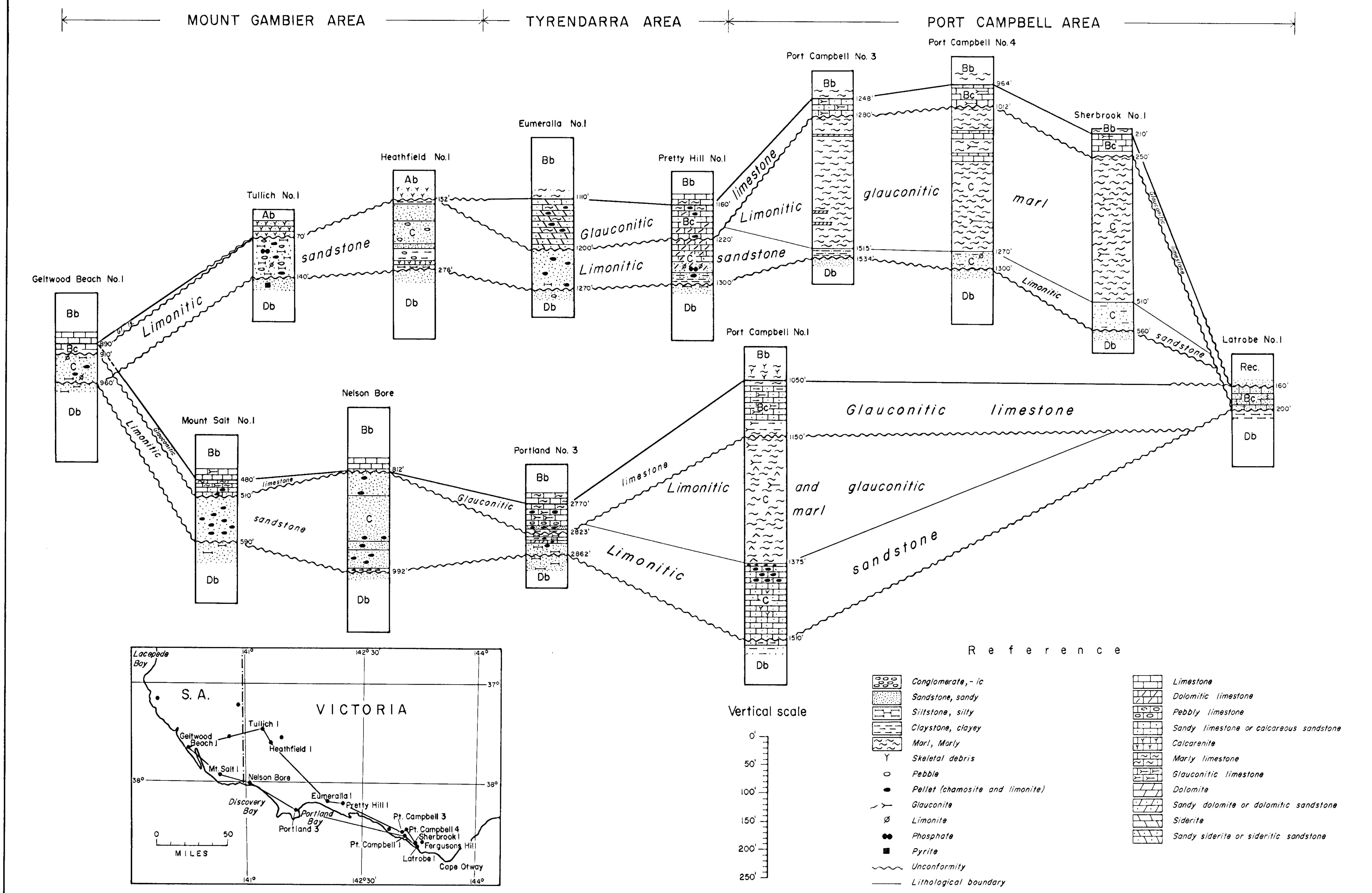
OTWAY BASIN
LITHOFACIES VARIATIONS OF PEBBLE POINT FORMATION
(No horizontal scale)



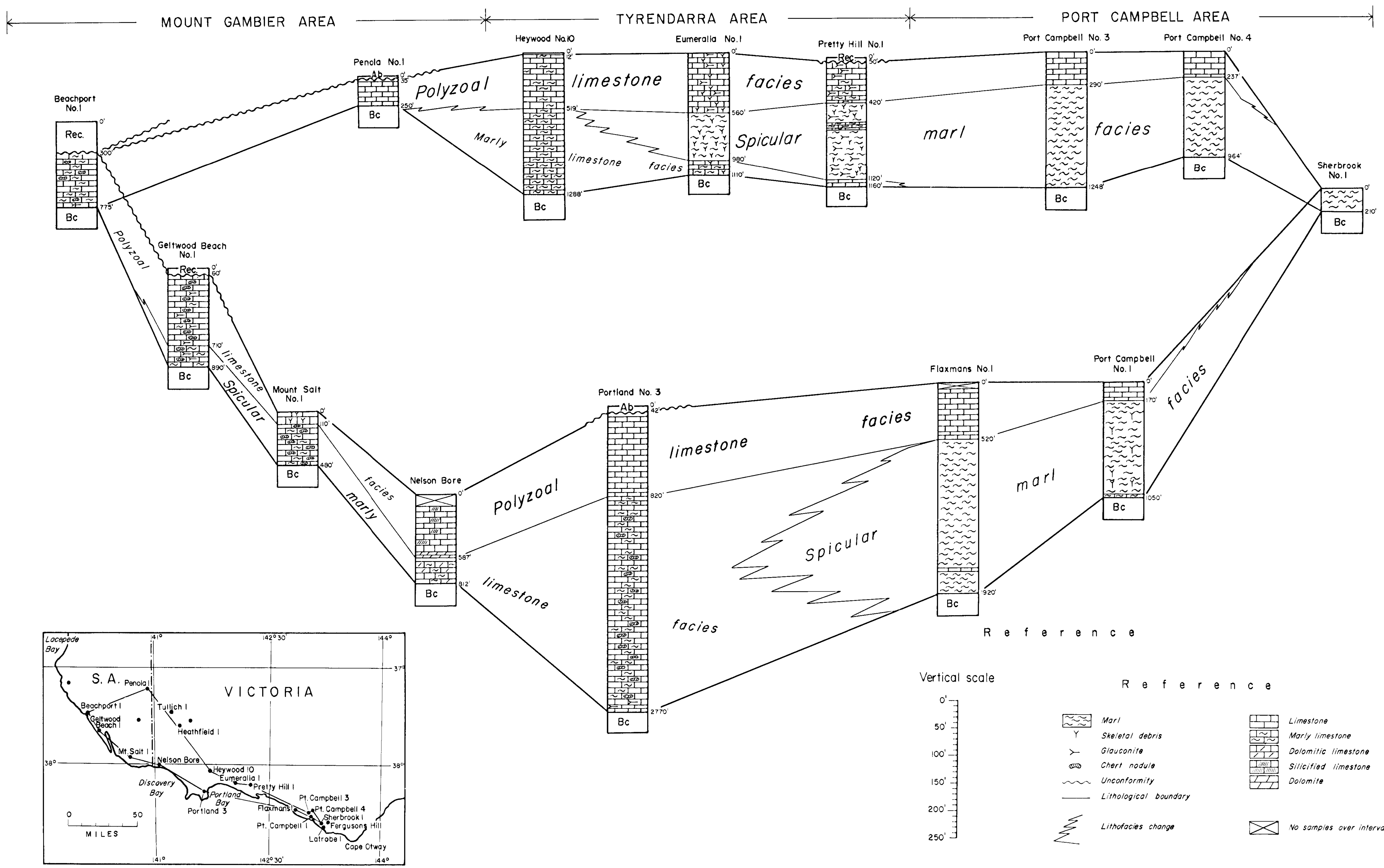
OTWAY BASIN

LITHOFACIES VARIATIONS OF UNIT Bc

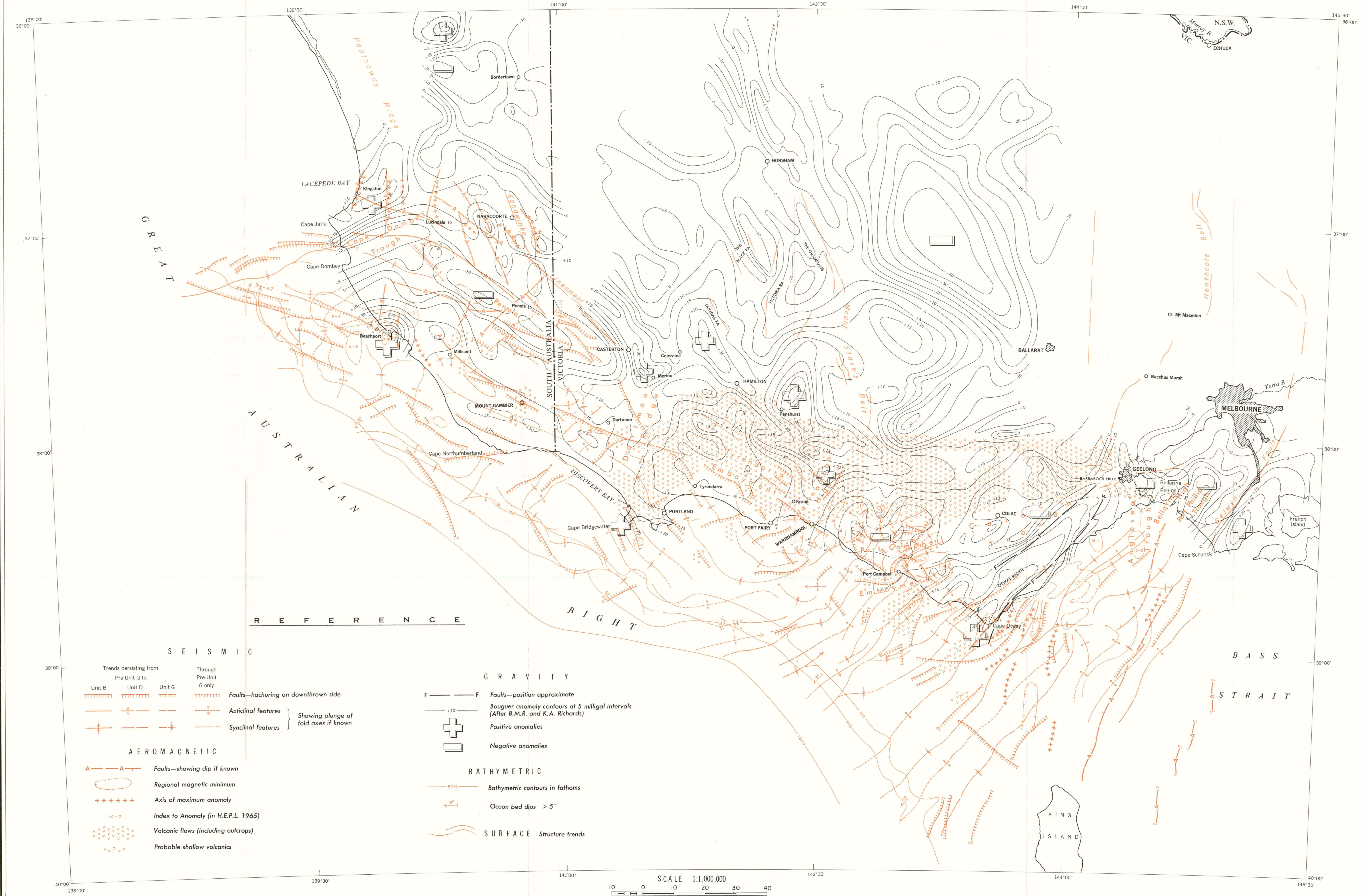
(No horizontal scale)



OTWAY BASIN
LITHOFACIES VARIATIONS OF UNIT Bb
(No horizontal scale)



SUBSURFACE STRUCTURE - OTWAY BASIN



B.M.R. Petroleum Exploration Branch, August, 1968

X AUS-1-378

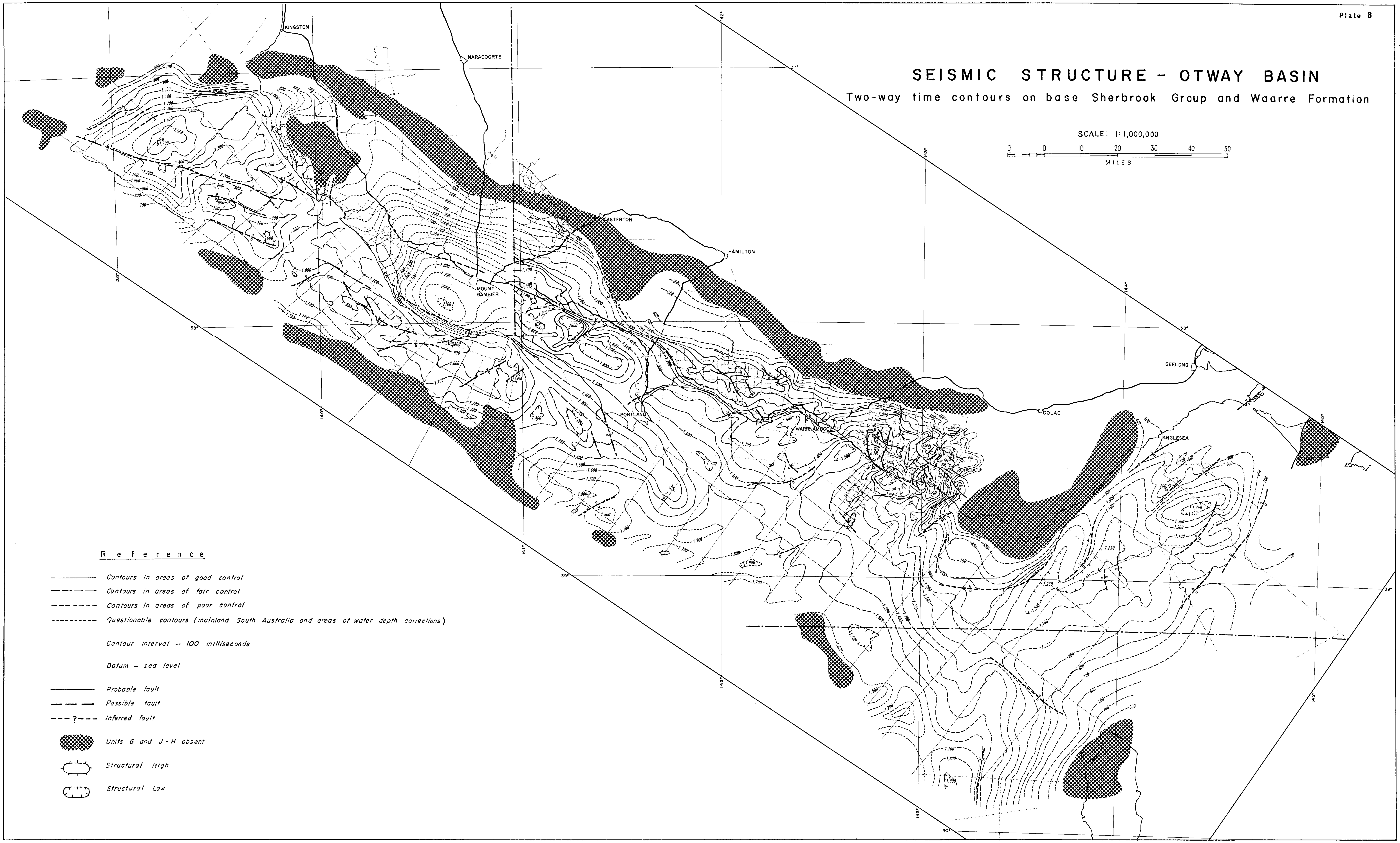
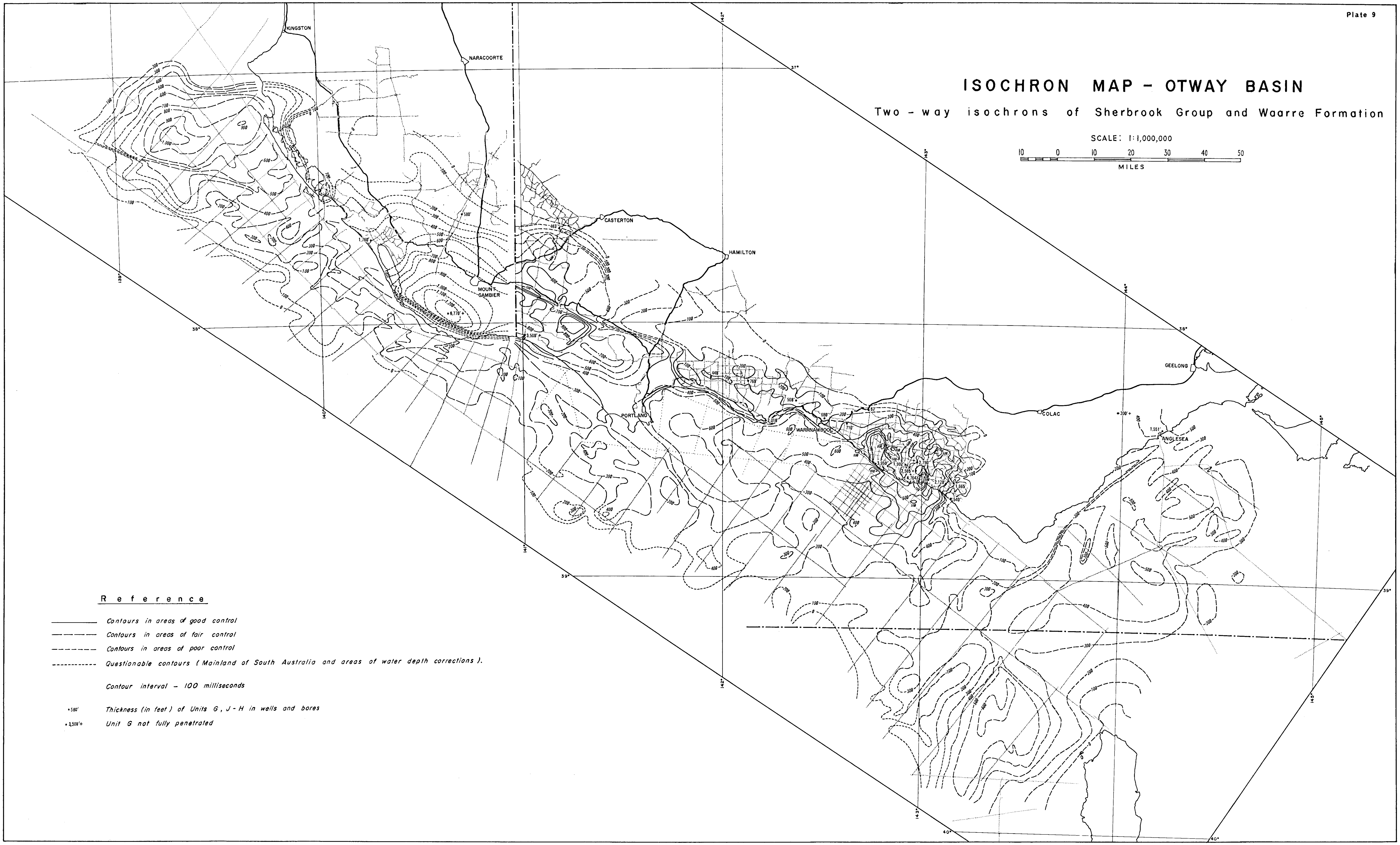

SEISMIC STRUCTURE - OTWAY BASIN
Two-way time contours on base Sherbrook Group and Waarre Formation
SCALE: 1:1,000,000
MILES
KINGSTON
NARACOORTE
CASTERTON
HAMILTON
MOUNT GAMBIER
PORTLAND
WARRNAMBOOL
COLAC
GEELONG
ANGLESEA
Reference
Contours in areas of good control
Contours in areas of fair control
Contours in areas of poor control
Questionable contours (mainland South Australia and areas of water depth corrections)
Contour interval - 100 milliseconds
Datum - sea level
Probable fault
Possible fault
Inferred fault
Units G and J-H absent
Structural High
Structural Low

Plate 9


ISOCHRON MAP - OTWAY BASIN
Two - way isochrons of Sherbrook Group and Waarre Formation
SCALE: 1:1,000,000
10 0 10 20 30 40 50
MILES
KINGSTON
NARACOORTE
CASTERTON
HAMILTON
MOUNT GAMBIER
PORTLAND
WARRNAMBOOL
COLAC
GEELONG
ANGLESEA
Reference
Contours in areas of good control
Contours in areas of fair control
Contours in areas of poor control
Questionable contours (Mainland of South Australia and areas of water depth corrections).
Contour interval - 100 milliseconds
580' Thickness (in feet) of Units G, J - H in wells and bores
3,500'+ Unit G not fully penetrated

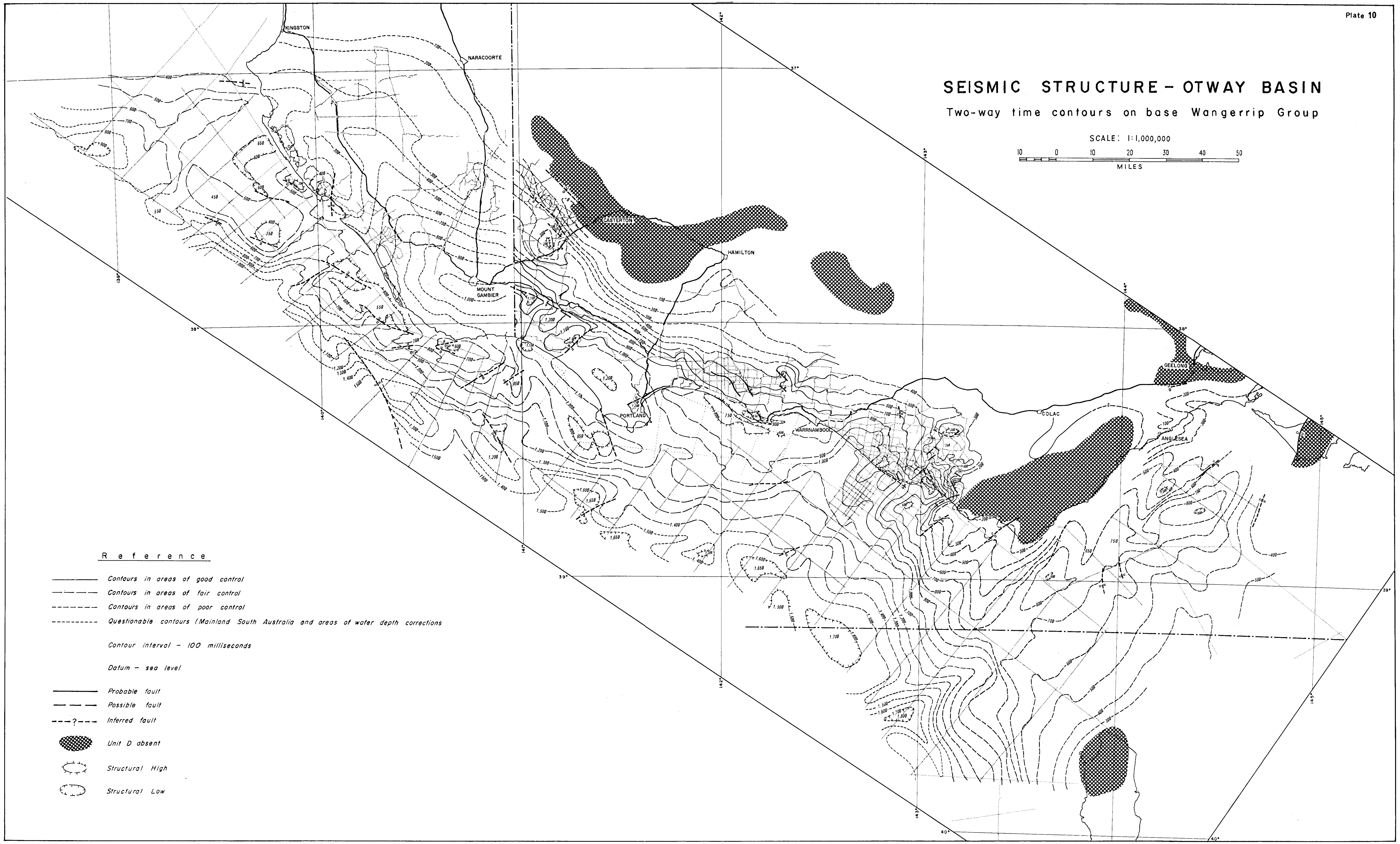


Plate 10
SEISMIC STRUCTURE – OTWAY BASIN
Two-way time contours on base Wangerrip Group
SCALE: 1:1,000,000
10 0 10 20 30 40 50
MILES
KINGSTON
NARACOORTE
CASTERTON
HAMILTON
MOUNT GAMBIER
PORTLAND
WARRNAMBOOL
COLAC
GEELONG
ANGLESEA
Reference
Contours in areas of good control
Contours in areas of fair control
Contours in areas of poor control
Questionable contours (Mainland South Australia and areas of water depth corrections
Contour interval – 100 milliseconds
Datum – sea level
Probable fault
Possible fault
Inferred fault
Unit D absent
Structural High
Structural Low

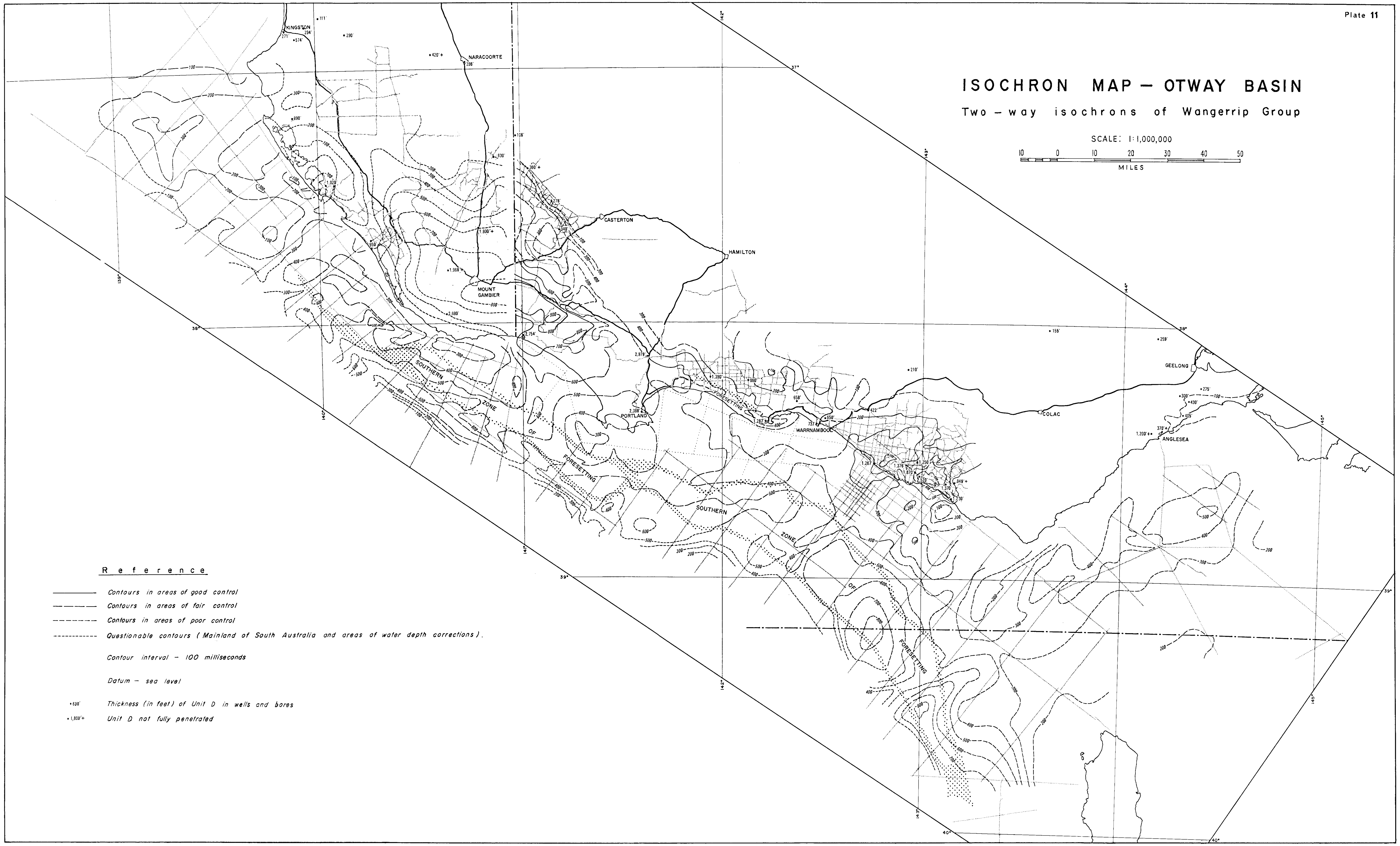


Plate 11
ISOCHRON MAP — OTWAY BASIN
Two — way isochrons of Wangerrip Group
SCALE: 1:1,000,000
10 0 10 20 30 40 50
MILES
Reference
Contours in areas of good control
Contours in areas of fair control
Contours in areas of poor control
Questionable contours (Mainland of South Australia and areas of water depth corrections).
Contour interval - 100 milliseconds
Datum - sea level
Thickness (in feet) of Unit D in wells and bores
Unit D not fully penetrated
KINGSTON
NARACOORTE
CASTERTON
HAMILTON
MOUNT GAMBIER
PORTLAND
WARRNAMBOOL
COLAC
GEELONG
ANGLESEA
SOUTHERN ZONE OF FORESETTING
FORESETTING

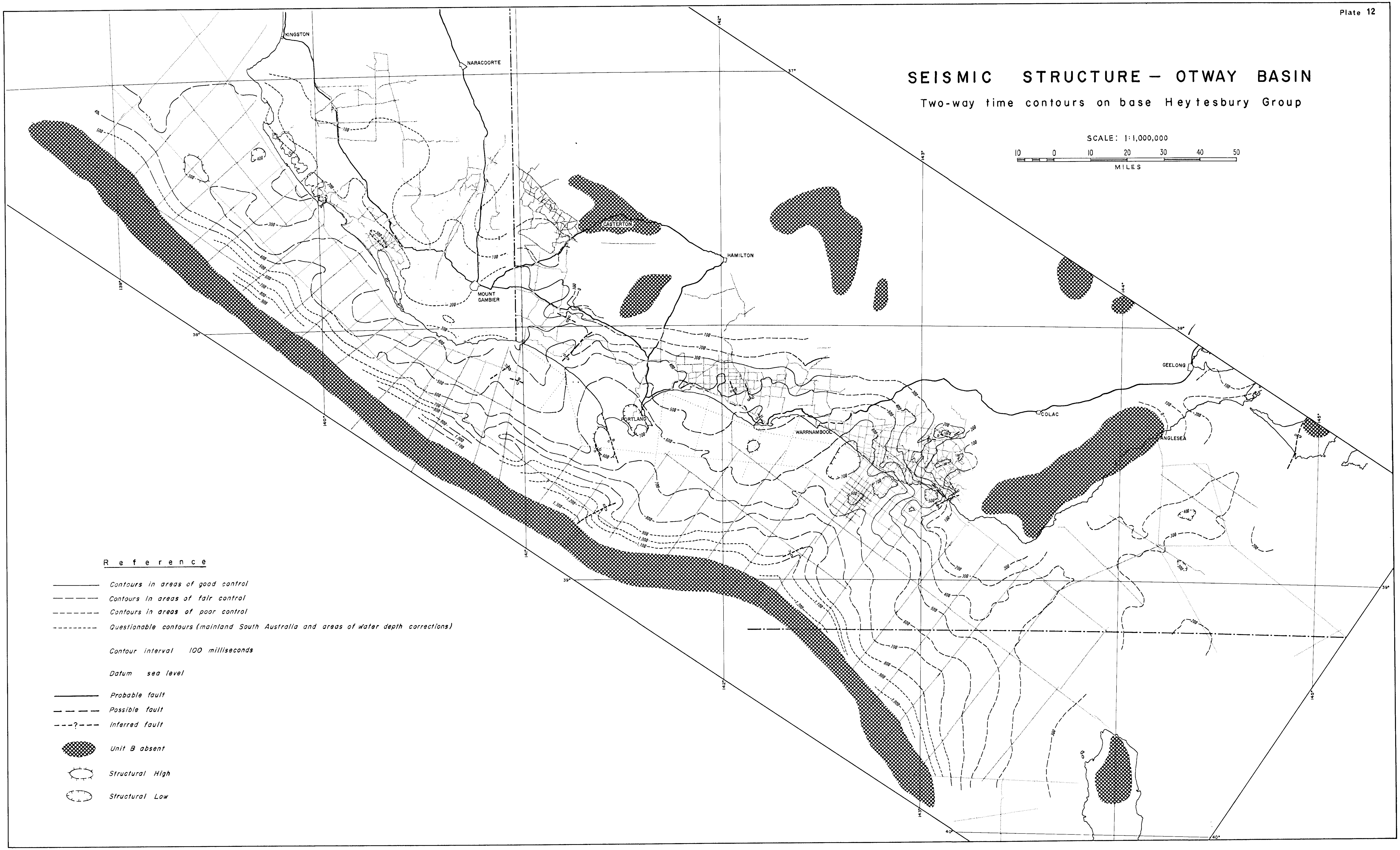
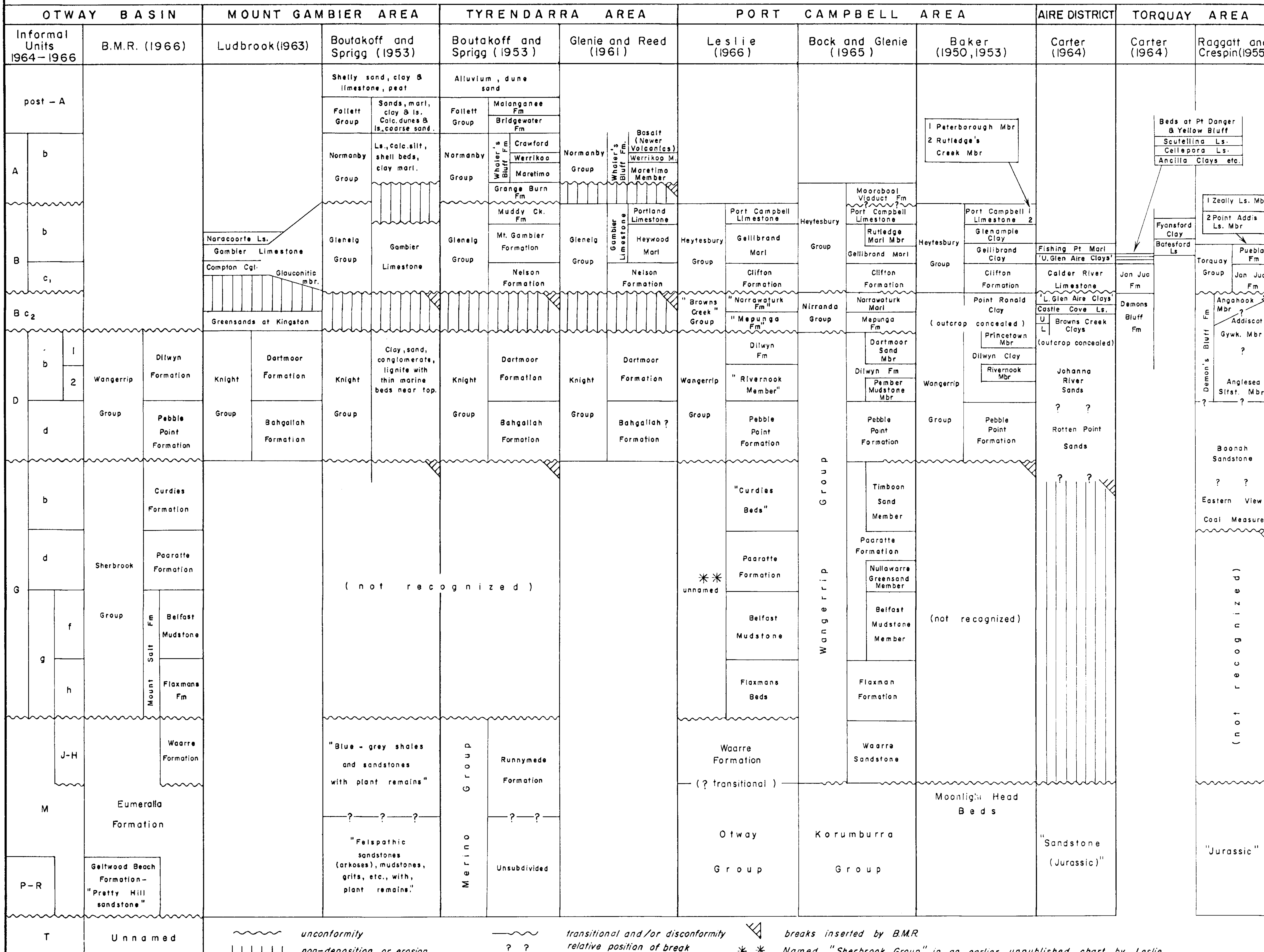


Plate 12
SEISMIC STRUCTURE — OTWAY BASIN
Two-way time contours on base Heytesbury Group
SCALE: 1:1,000,000
10 0 10 20 30 40 50
MILES
KINGSTON
NARACOORTE
CASTERTON
HAMILTON
MOUNT GAMBIER
PORTLAND
WARRNAMBOOL
COLAC
GEELONG
ANGLESEA
Reference
Contours in areas of good control
Contours in areas of fair control
Contours in areas of poor control
Questionable contours (mainland South Australia and areas of water depth corrections)
Contour interval 100 milliseconds
Datum sea level
Probable fault
Possible fault
Inferred fault
Unit B absent
Structural High
Structural Low

Chart 1

COMPARISON OF STRATIGRAPHIC NOMENCLATURE FROM THE OTWAY BASIN



Bureau of Mineral Resources, Geology and Geophysics. December 1966.

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