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

BULLETIN 97

Upper Palaeozoic Rocks, Bonaparte Gulf Basin of Northwestern Australia

BY

J. J. VEEVERS and J. ROBERTS

Issued under the Authority of the Hon. David Fairbairn
Minister for National Development
1968

COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

MINISTER: THE HON. DAVID FAIRBAIRN, D.F.C., M.P.

SECRETARY: R. W. BOSWELL, O.B.E.

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

DIRECTOR: J. M. RAYNER, O.B.E.

THIS BULLETIN WAS PREPARED IN THE GEOLOGICAL BRANCH

ASSISTANT DIRECTOR: N. H. FISHER

Published by the Bureau of Mineral Resources, Geology and Geophysics

Canberra, A.C.T.

Printed by Graphic Services Pty. Ltd., Adelaide

CONTENTS

APPENDIXES

TABLES

ILLUSTRATIONS

FIGURES

SUMMARY

The Bonaparte Gulf Basin is a broad north-pitching syncline of Phanerozoic sediments which extends from northwestern Australia beneath the Timor Sea. The landward part of the basin is divided into two parts by Queens Channel. Except for two incomplete well sections in the area north of Queens Channel, the Upper Devonian and Lower Carboniferous sedimentary rocks are known only in the southern part of the basin, where the sequence cropping out comprises a complex of 12,000 feet of conglomerate, quartz sandstone, limestone, siltstone, and shale; the sequence unconformably overlies Precambrian, Cambrian, and Lower Ordovician rocks, and is unconformably overlain by Upper Carboniferous and Permian sediments. An equivalent Upper Devonian and Lower Carboniferous sequence of medium-grey siltstone, shale, and minor sandstone, at least 14,000 feet thick, is found in deep wells in the central part of the basin. Both sequences were deposited on a marine shelf: the out-cropping sequence on a platform and the subsurface sequence in a slightly deeper basin.

During two periods of faulting along the eastern margin in the Frasnian, thick conglomerate was deposited along the landward margin, and quartz sandstone over the rest of the platform. Between the faulting in the Frasnian, and during the entire Famennian, the supply of coarse terrigenous sediment was reduced, and carbonate reef complexes were deposited on the northwestern part of the platform. Reef deposition on the northwestern platform probably persisted into the early Tournaisian. Slightly later, the northwestern platform was tilted, faulted, uplifted, and eroded and, still within the Tournaisian, the sea returned, and breccia was deposited along the shore. In contrast, the southeastern platform was uplifted and eroded at the end of the Upper Devonian, and was covered again by the sea in the Tournaisian, during which two alterations of calcarenite and quartz sandstone, with a total thickness of 3,000 feet, were deposited.

Shale covered the entire platform during the early Visean, and was succeeded on the northwestern platform by calcarenite. The platform was then uplifted and eroded until late in the Visean, when breccia and coarse calcareous sandstone were deposited in an advancing sea. This sea remained at least until the late Visean or early Namurian. The whole platform was then uplifted and eroded, and in the Upper Carboniferous was covered by a few hundred feet of continental sandstone, conglomerate, and siltstone, which was the first deposit of paralic sequence which continued through the Permian into the Lower Triassic.

Little is known of the depositional environment of the Upper Devonian and Lower Carboniferous shale, siltstone, and minor sandstone equivalent to the platform sequence, which were deposited in the deeper part of the shelf.

In the Permian, step faults along the eastern margin were reactivated, and the eastern upthrown blocks were subsequently deeply eroded.

Stratigraphical and structural traps in the hinge between the platform and basinal sediments are the most attractive places to seek petroleum.

Page 2 is blank.

INTRODUCTION

The Bonaparte Gulf Basin is a north-pitching syncline of Phanerozoic sediments, which are bounded to the south by Precambrian rocks and extend northward beneath the Timor Sea (Fig.1). The landward part of the basin has been fragmented by faults, uplift, and erosion into a main outcrop area and three outliers. The eastern edge of the original depositional basin corresponds approximately with the present eastern margin, but the original extent to the south and west is unknown. Within the main outcrop is a Precambrian inlier, the Pincombe Inlier, which influenced deposition during the Upper Devonian and Lower Carboniferous. The main outcrop (Fig. 2) comprises Lower Cambrian volcanics, and Cambrian, Lower Ordovician, Upper Devonian, Carboniferous, Permian, Lower Triassic, and Lower Cretaceous sediments. The outliers contain only the lower part of this sequence, up to and including the lower part of the Upper Devonian.

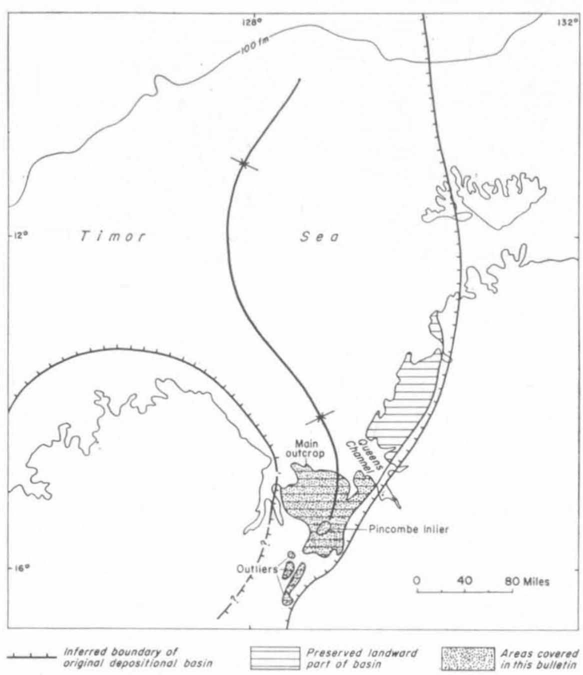


Figure 1. Bonaparte Gulf Basin: inferred outlines of the original depositional basin, the preserved part of the basin on land, and the areas covered by this Bulletin. Structural axis and seaward extent of basin after Jacquemin (1966)

The full sequence can be divided on the basis of depositional environment into two parts (Fig. 3): (a) 16,000 feet of Cambrian to Lower Ordovician and Upper Devonian to Lower Carboniferous shallow-marine quartz sandstone and carbonate rocks, with known equivalent deeper marine grey siltstone in the Upper Devonian and Lower Carboniferous; and (b) 7,000 feet of Upper Carboniferous to Lower Triassic paralic sandstone and shale, capped by a few hundred feet of Lower Cretaceous marine siltstone, sandstone, and conglomerate.

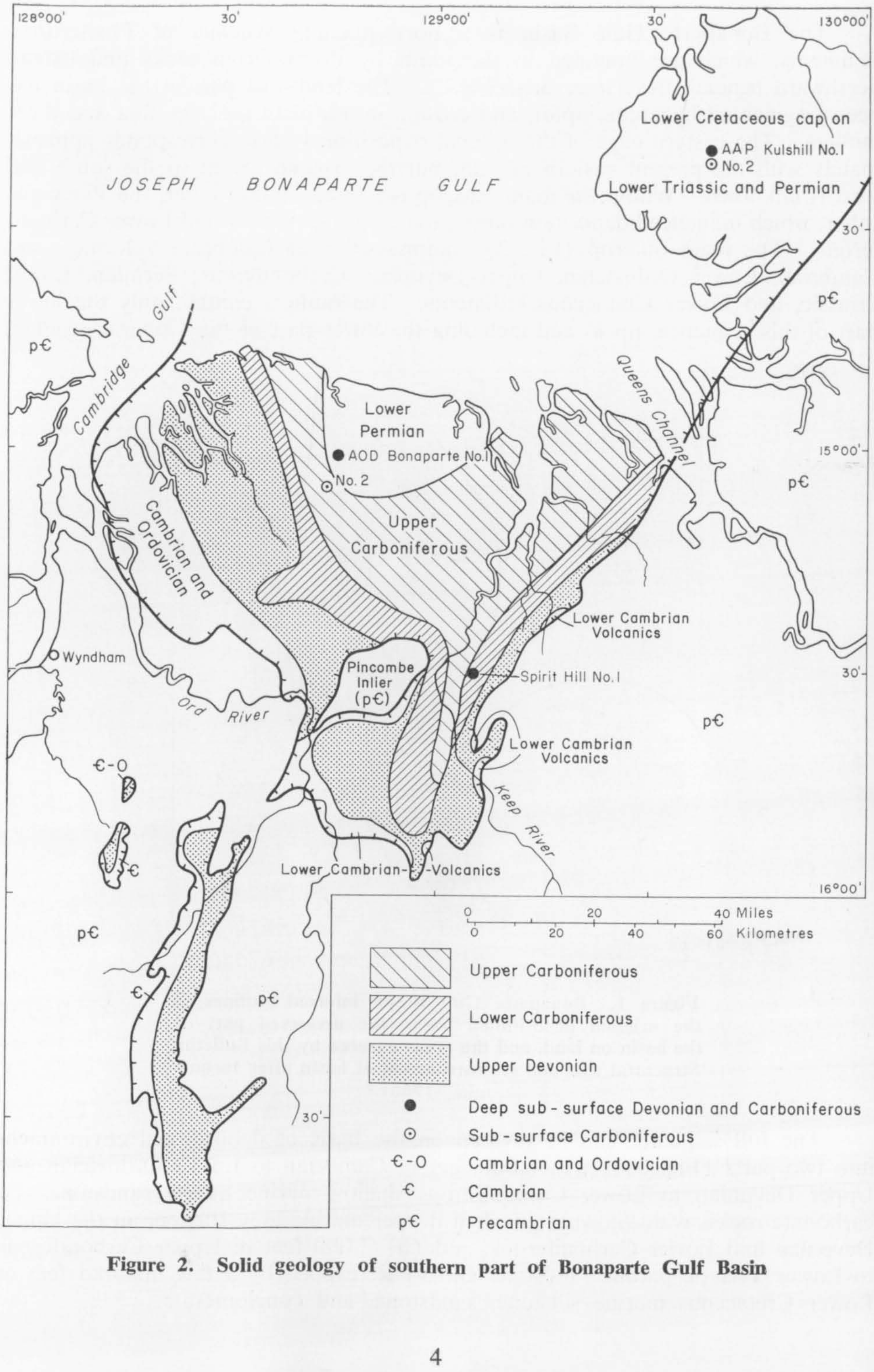


Figure 2. Solid geology of southern part of Bonaparte Gulf Basin

Most of our work has been done in the well exposed Upper Devonian and Carboniferous part of the sequence, which is the subject of this Bulletin. Except in two wells (Kulshill Nos 1 & 2) north of Queens Channel, these sediments are known in outcrop and subsurface from the southern part of the basin only, and this Bulletin, and the report on the Cambrian and Lower Ordovician geology by Kaulback & Veevers (1968), describe the geology of the southern Bonaparte

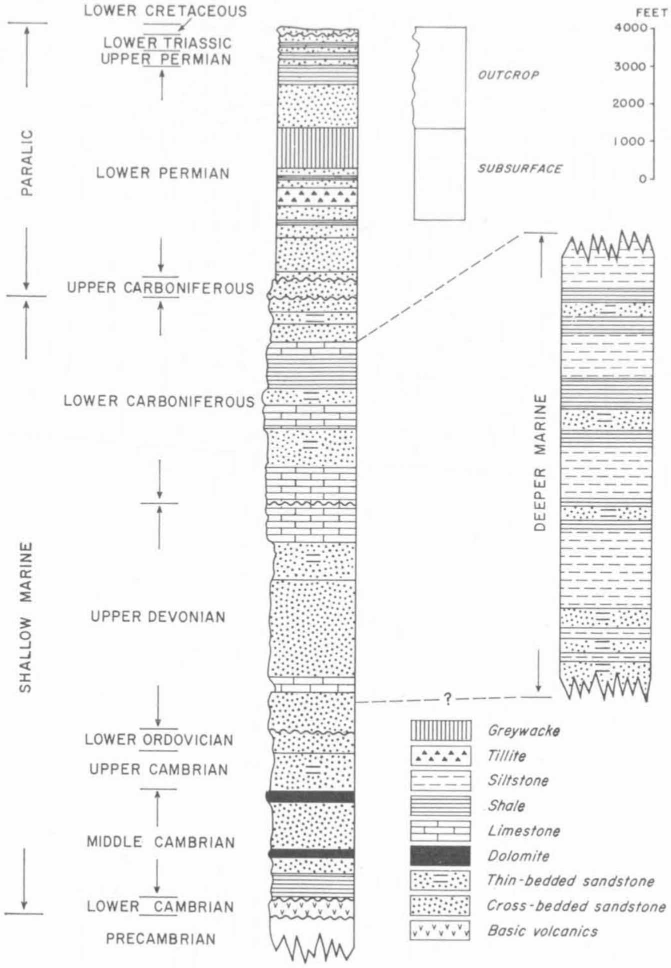


Figure 3. Diagrammatic composite stratigraphical sections, Bonaparte Gulf Basin

Gulf Basin. The Permian and Mesozoic part of the basin, virtually all of which lies north of Queens Channel, is to be described by Dickins, Roberts, & Veevers (in prep.). Van Andel & Veevers (1967) have described the sediments and morphology of the Timor Sea, and Jacquemin (1966), Smith (1966), Veevers (1967a), and Veevers & Van Andel (1967) have dealt with the structure of the seaward part of the Bonaparte Gulf Basin. A geological review of the north-western Australian region, of which the Bonaparte Gulf Basin is a part, is given by Veevers (1967b).

The stratigraphical relationships of the Devonian and Carboniferous formations are given in a generalized correlation diagram (Fig. 4). Detailed correlations between measured sections are shown in various figures, and are summarized in Figure 40. These figures show a number of breaks in the sedimentary record. Structurally, the rocks in the Bonaparte Gulf Basin are only slightly deformed, and most are gently dipping or flat-lying. Folds are rare and the main structural elements are faults. Most of the breaks are *disconformities,* as defined by Dunbar & Rodgers (1957), where there is an obvious erosional break between essentially parallel strata; other breaks recognized within the basin include *para-*

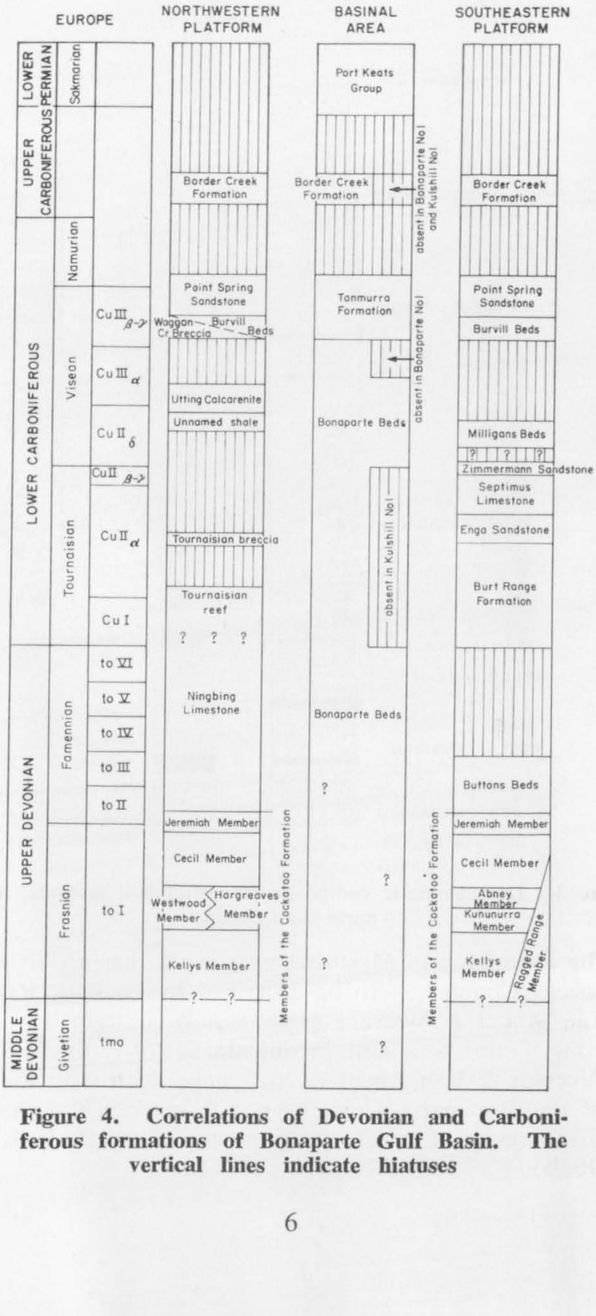


Figure 4. Correlations of Devonian and Carboniferous formations of Bonaparte Gulf Basin. The vertical lines indicate hiatuses

Plate 1. Aerial view, looking northeast, of the Ord River diversion dam, taken in wet season during construction. The dam rests on a bar of Precambrian quartzite, Bandicoot Bar. Kununurra is on the right of the field of view, in front of Kellys Knob and the sandstone scarp which is visible up to Abney Hill. Behind and to the left of Abney Hill is the Pincombe Range. The dome on the right-hand skyline is Mount Cecil

Plate 2, Figure 1. Ragged Range Conglomerate Member at Church Steeple Peak (loc. 412-2). Band of fairly well-sorted pebbles sandwiched between beds of cobble and boulder conglomerate. Pelecypods were found in the pebbly sandstone immediately overlying the conglomerate

Plate 2, Figure 2. Same locality as Fig. 1. Poorly sorted rounded cobbles and boulders of quartzite and a large boulder of basalt

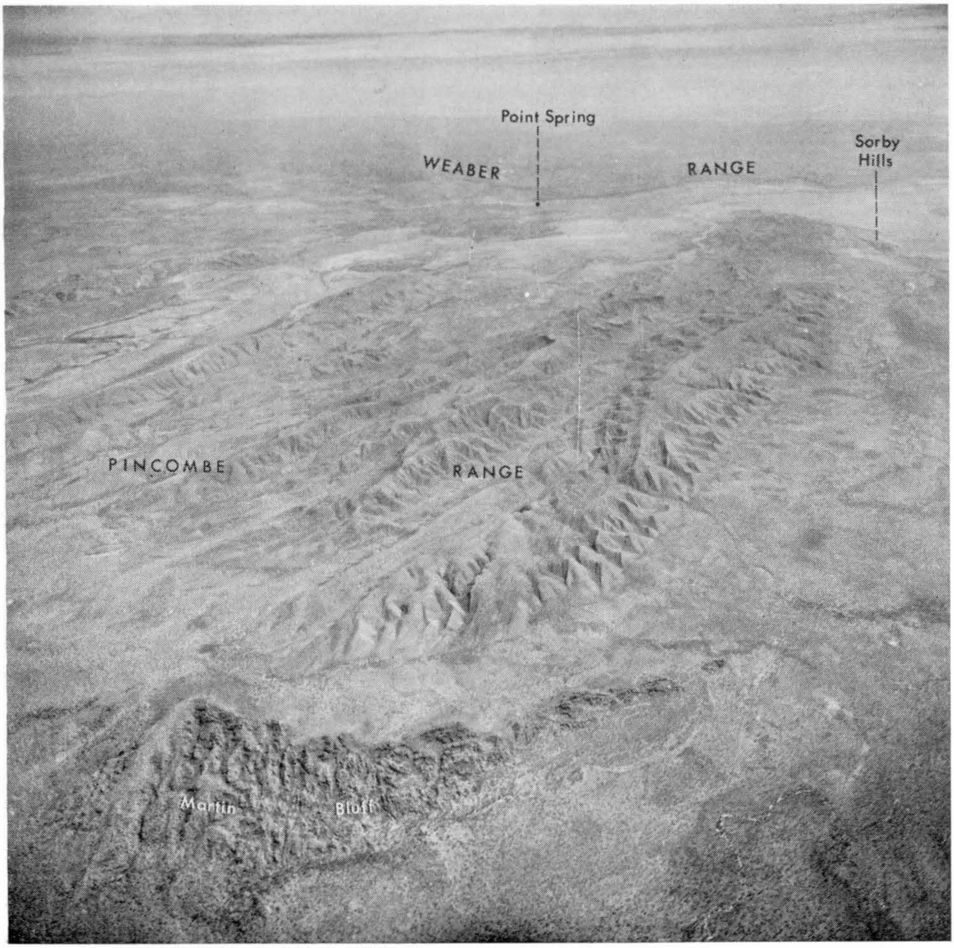


Plate 3. Oblique air-photograph, looking north at Antrim Plateau Volcanics overlain by Cockatoo Formation in Martin Bluff, and steep-dipping Precambrian sandstone and siltstone of the Pincombe Range. The scarp of the Weaber Range is visible beyond the Pincombe Range

Plate 4, Figure 1. Looking north at Abney Hill. The scarp is a fault. Left of the fault (locality 438) the Kellys Knob Member (rough outcrop) is overlain by the Kununurra Member (smooth dark outcrop); right of the fault, the Kellys Knob Member is paraconformably overlain by the Abney Member

Plate 4, Figure 2. Looking northeast down dipslope of Kellys Knob Member on Matheson Ridge. The Kununurra and Abney Members are indicated by the smooth ground in the middle distance, and are overlain by the Cecil Member. Enga Ridge is on the skyline

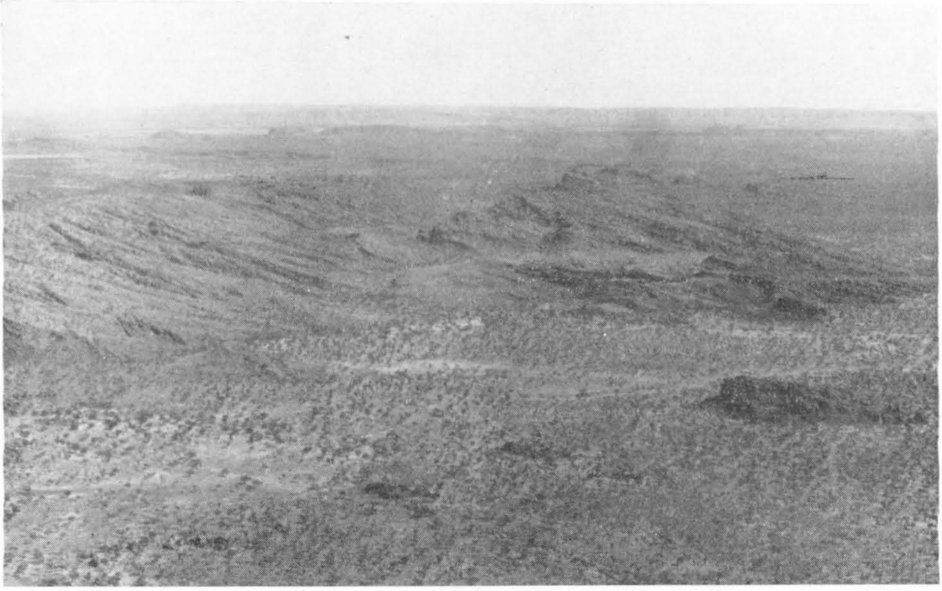


Plate 5, Figure 1. Looking northwest along the strike at Matheson Ridge. Rough dipslope of Kellys Knob Member on left, smooth ground of Kununurra and Abney Members in middle, and rough scarp and dipslope of Cecil Member on right

Plate 5, Figure 2. Conglomeratic sandstone of the Abney Member at Matheson Ridge (locality 28-12). The largest boulders are 12 inches (30 cm) long

Plate 6. Oblique air-photograph, looking slightly east of north of the Cockatoo Fault. Enga Ridge and central Burt Range in the middle distance, and Keep Inlet on the horizon. For details see Figure 14. cf fig. 28 of Traves (1955)

conformities (Dunbar & Rodgers, 1957), established on the basis of fossils, and *angular unconformities*. Where the exact nature of the break is unknown it is termed an *unconformity*.

Brief accounts of the geological history of the Upper Devonian and Carboniferous are given on pages 132 to 137.

This work is the first published detailed revision of Traves' (1955) work in the southern Bonaparte Gulf Basin. Since Traves' report appeared, much geological and geophysical work and the first deep drillings (Spirit Hill No. 1, Bonaparte Nos 1 & 2, and Kulshill Nos 1 & 2) have been done; appropriate references to this unpublished work have been incorporated in the text. A comprehensive account of geological work carried out up to 1962 is given by Drummond (1963). Guillaume (1966) has summarized work carried out by Australian Aquitaine Petroleum Pty Ltd. A general summary appeared in Brady, Jauncey, & Stein (1966).

The field work in the Upper Devonian and Carboniferous sequence was done by Veevers and Roberts during 1963 and 1965. P. J. Jones and E. C. Druce spent short periods in the field collecting micropalaeontological samples. The sequence is abundantly fossiliferous, and the principal groups of fossils are being studied by the following: brachiopods, J. Roberts; ostracods and, in the initial stages, conodonts, P. J. Jones (1968); conodonts, E. C. Druce (1968); foraminifers, D. J. Belford, in collaboration later with Professor B. L. Mamet (Univ. of Montreal); algae and trace fossils, J. J. Veevers; plants, Mrs Mary E. White; pollen and spores, Dr G. Playford (Univ. of Queensland); fish, Joyce G. Tomlinson; corals, Dr J. S. Jell (Univ. of Queensland).

Veevers (BMR Bull. 109, in prep.) is studying the sedimentology of the sequence, and Dr F. C. Loughnan (Univ. of NSW) has examined the mineralogy of the clays in selected bores (in BMR Record 1966/113). The results of this specialized work, which is still in progress, will be published separately, but have been freely drawn on in this Bulletin.

During this investigation, we have co-operated closely and exchanged information with interested oil prospecting companies, in particular Australian Aquitaine Petroleum Pty Ltd.

Some preliminary results have already been published by Veevers et al. (1964), Playford et al. (1966), and Jones & Druce (1966). The Waggon Creek Breccia was described by Veevers & Roberts (1966). Summaries of our work were presented to international conferences in 1967 (Veevers & Roberts, 1967; Roberts, Jones, & Druce, 1967; Roberts & Veevers, 1967). J. Hays (BMR) made a brief visit to the area in 1965 and is responsible for the outline of the geomorphology on pages 138-140.

Previous Work

Previous work is referred to in appropriate places in the text. A compilation of work carried out up to December 1962 was made by Drummond (1963). Mr E. P. Utting's unpublished work was particularly useful to us.

The oil exploration wells and stratigraphic bores drilled in the area are listed in Table 1.

TABLE 1: OIL EXPLORATION WELLS AND STRATIGRAPHIC BORES

Name	Drilled by (Date)	Total Depth (ft)	Location
Oil Exploration Wells			
Spirit Hill No. 1	Westralian Oil Ltd (1959); completed by Oil Development N.L. (1960)	3,003	1 mile N of Spirit Hill
Bonaparte No. 1	Alliance Oil Development Australia N.L. (1963)	10,530	16 miles ENE of Ningbing station
Bonaparte No. 2	Alliance Oil Development Australia N.L. (1964)	7,008	5 miles SW of Bonaparte No. 1
Kulshill No. 1	Australian Aquitaine Petroleum Pty Ltd (1965-66)	14,416	9 miles S of Port Keats Mission
Kulshill No. 2	Australian Aquitaine Petroleum Pty Ltd (1966)	6,433	12 miles S of Port Keats Mission
Stratigraphic Bores			
Milligans No. 1 Bore ..	Westralian Oil Ltd (1956)	520	SE corner of Milligans Hills
Milligans No. 2 Bore ..	Westralian Oil Ltd (1956)	186	2 miles NE of Milligans Hills
Milligans No. 3 Bore ..	Westralian Oil Ltd (1956)	90	3 miles NNE of Milligans Hills
Spirit Hill No. 1 Bore	Westralian Oil Ltd (1956)	295	S margin of Spirit Hill
Spirit Hill No. 2 Bore	Westralian Oil Ltd (1956)	252	
Spirit Hill No. 3 Bore	Westralian Oil Ltd (1956)	201	

Location and Access

The area described lies on either side of the border between Western Australia and Northern Territory, behind the southern shore of the Joseph Bonaparte Gulf (Fig. 5). It is bounded in the northwest by Cambridge Gulf, and by Queens Channel in the northeast. The area is covered by parts of the Medusa Banks, Cambridge Gulf, Lissadell, Auvergne, and Port Keats 1:250,000 Sheets. It contains two towns: the port of Wyndham, which is a centre for the cattle-raising industry, and Kununurra, the centre of the Ord River Irrigation Scheme (Pl. 1). Both are linked to Perth and Darwin by regular air services, and Wyndham by regular shipping services. The Great Northern Highway and the Wyndham-Nicholson road cross the area, and numerous tracks serve the cattle stations. The irrigated farming area north of Kununurra has a close network of roads.

Climate

The area has a warm monsoonal climate with a short rainy season in summer and a long dry season (or drought) in winter. The annual rainfall is about 30 inches and, compared with areas farther inland, is reliable. Temperature is high throughout the year: Wyndham has the highest recorded mean temperature in Australia of 84°F. Further details are provided by Traves (1955).

Topography

Except for the Burt Range, the whole area lies within the Cambridge Gulf Lowlands (Traves, 1955, fig. 6). The elevation ranges from sea level to 1,012 feet in the Burt Range. The area is drained by the lower reaches of the Ord and Keep Rivers.

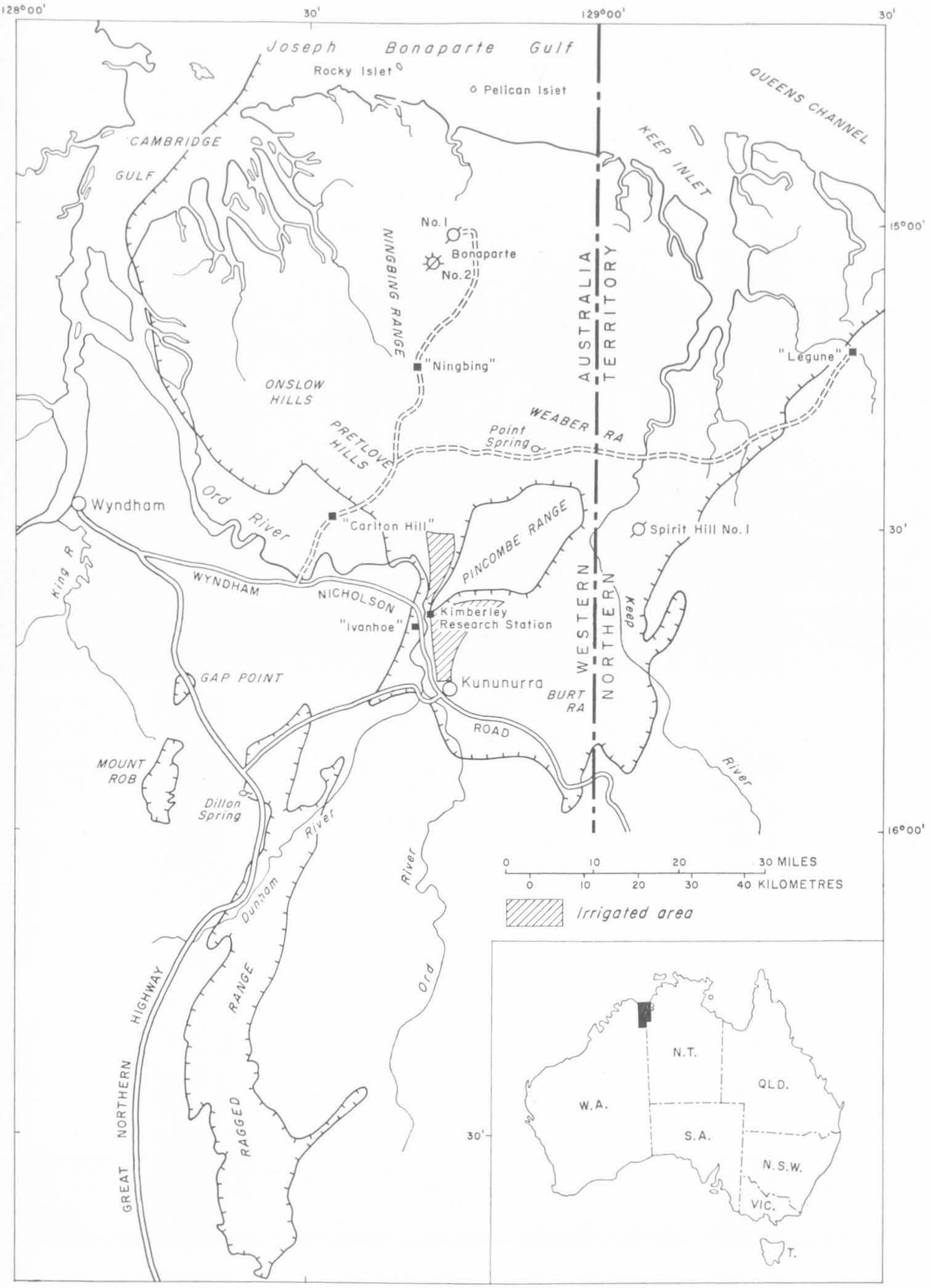


Figure 5. Bonaparte Gulf Basin, location and access

Air-Photographs

The area is covered by 1:50,000 vertical air-photographs taken by the Royal Australian Air Force in 1948, and part is covered by trimetrogon air-photographs taken in 1944. The area of the Ord River Scheme and neighbouring areas (Spirit Hill, and part of the Weaber Range) are covered by 1:16,000 vertical air-photographs taken in 1961. Before field work started, photogeological maps were prepared by R. Ruker, R. Richard, and W. J. Perry, of the Bureau of Mineral Resources. Richard also briefly visited us in the field.

Field Methods

In addition to the photogeological maps, Ruker, Richard, and Perry supplied overlays showing their interpretations. The overlays and the accompanying photographs provided the base for mapping. The overlays have been added to and modified by field observations, and were later reduced to compile the maps accompanying this Bulletin.

The thickness of well exposed sections was measured by means of an Abney level attached at right angles to a 5-foot Jacob staff (Robinson, 1959). In 1965, field sections were plotted directly on a strip log, using a device described by Veevers & Jackson (1966).

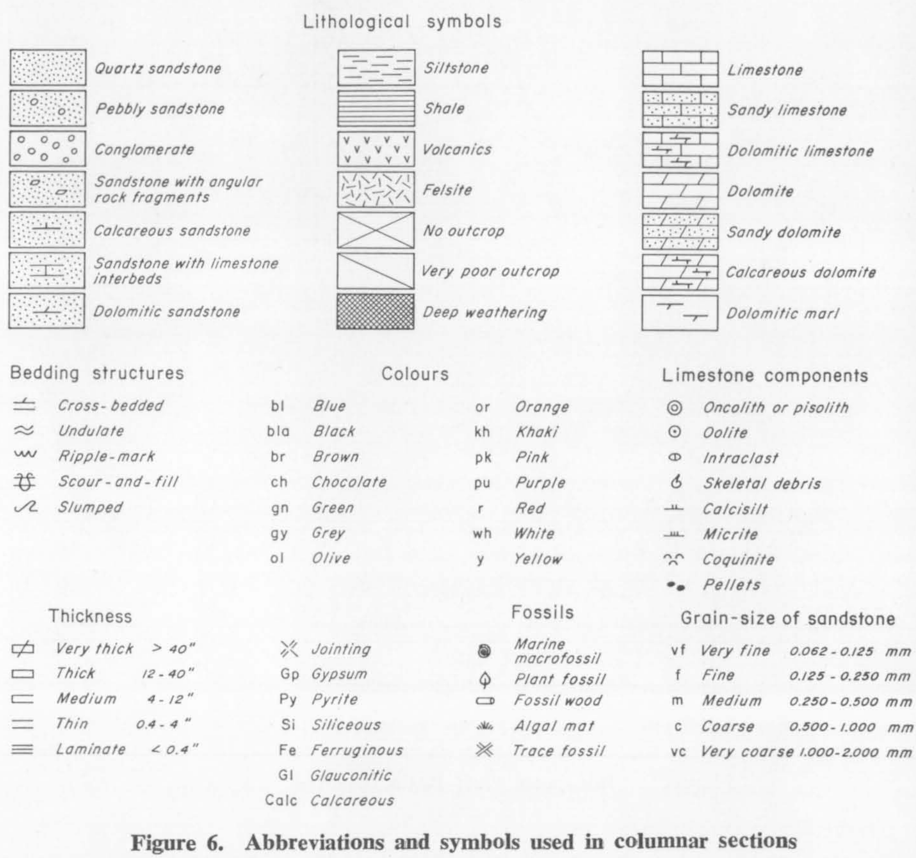


Figure 6. Abbreviations and symbols used in columnar sections

Numerous stratigraphical sections (aggregating about 50,000 ft) were measured and described; many of them are presented in graphic form in this Bulletin. The symbols and abbreviations used in the sections are listed in Figure 6. The sections are descriptive only: for example, only those unconformities and disconformities which are visible in the sections are shown.

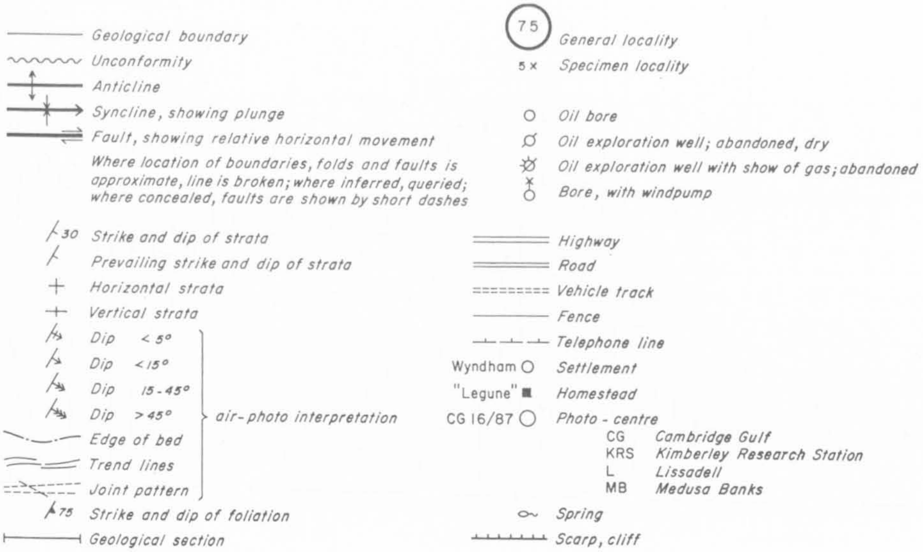


Figure 7. Symbols used on maps

Figure 7 is a legend to the maps and Figure 8 is a key diagram of detailed maps.*

PRE-UPPER DEVONIAN

The Upper Devonian/Lower Carboniferous sequence unconformably overlies Precambrian rocks, mainly sediments, Lower Cambrian volcanics (Antrim Plateau Volcanics), and Middle and Upper Cambrian and Lower Ordovician sediments. The Cambrian and Ordovician sediments (Fig. 9), which are not found east of a line joining Point Spring and the Ragged Range, are quartz sandstone, some glauconitic and hematitic, and minor dolomite and shale. The original description of these sediments by Traves (1955) has been amplified by Kaulback & Veevers (1968). The Antrim Plateau Volcanics (Fig. 9) are widespread in the Bonaparte Gulf Basin and its outliers, and in the region to the east and southeast (Traves, 1955). In the Bonaparte Gulf Basin, the Antrim Plateau Volcanics consist almost exclusively of amygdaloidal basalt, which is probably nowhere thicker than a few hundred feet. The Precambrian sequence in the Western Australian part of the region is currently being studied by the Bureau of Mineral Resources and the Geological Survey of Western Australia, and in the Northern Territory part by

* *Figures 6 and 7 are also included in the envelope at the back of the Bulletin, for ease of reference.*

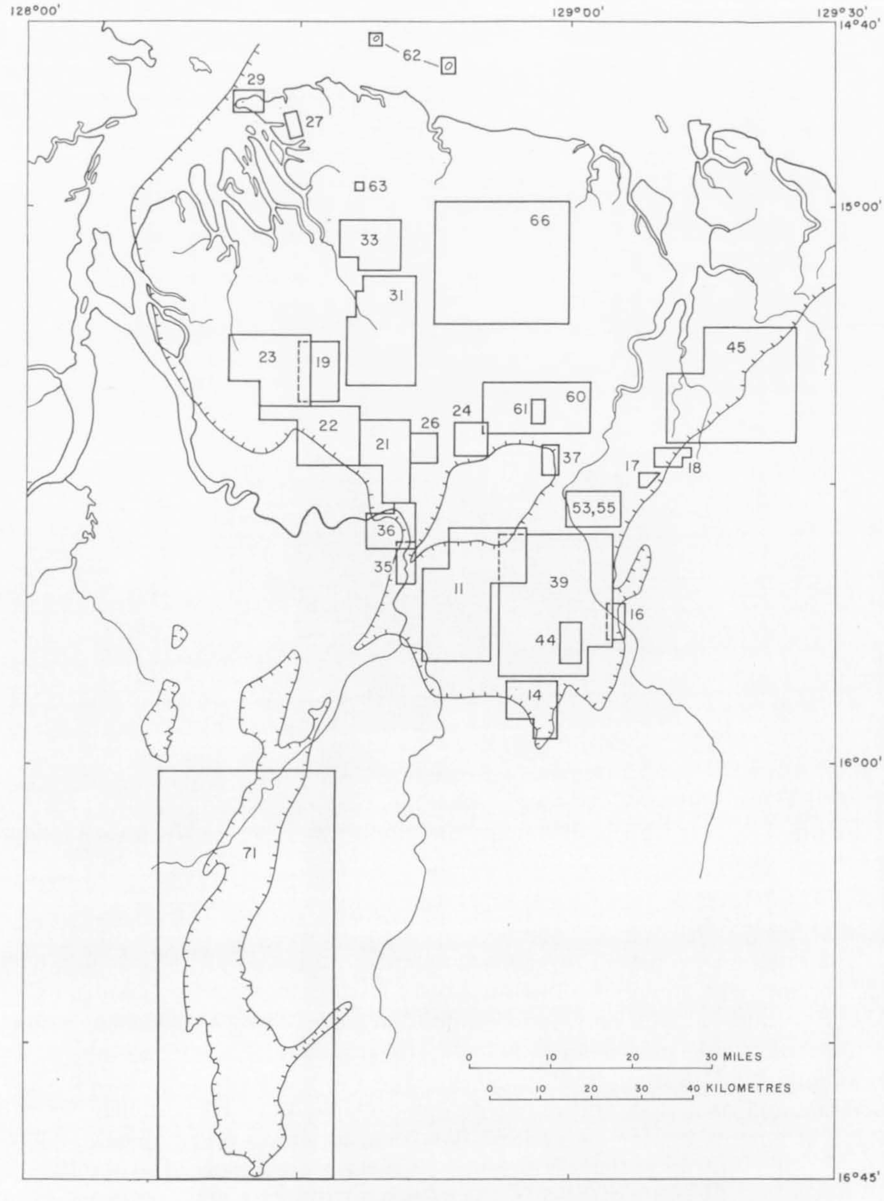


Figure 8. Key diagram of maps

the Bureau of Mineral Resources. The following notes, supplied by K. A. Plumb(BMR), are intended to serve as a sketch of the Precambrian geology of the area bordering the Bonaparte Gulf Basin.

Widespread outcrops of the Precambrian basement rocks enclose the Palaeozoic Bonaparte Gulf Basin in the east, south, and west (Fig. 9). They can be divided into two main groups: an ancient complex of plutonic and metamorphic rocks, and unconformably on it a succession of sedimentary rocks which are generally gently tilted.

The plutonic rocks crop out in the Halls Creek Mobile Zone, a linear belt about 30 miles wide, which extends in a north-northeasterly direction from Halls Creek in the south to near the Ord River Damsite, and then continues into the Northern Territory, roughly along the eastern margin of the Bonaparte Gulf Basin.

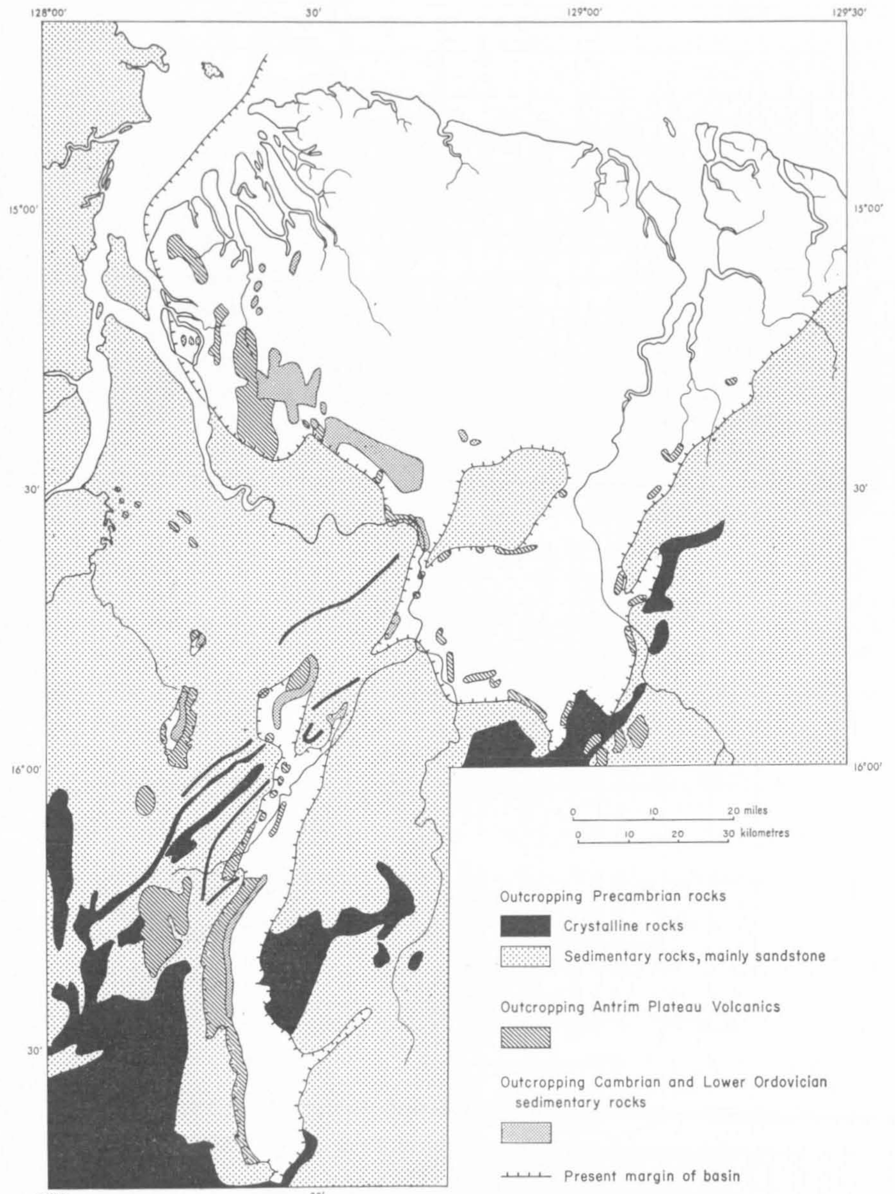


Figure 9. Distribution of pre-Upper Devonian rocks

The Precambrian rocks comprise metasediments and volcanics ranging from the greenschist to granulite facies, and associated granite gneiss, gabbro, ultrabasic rocks, and massive granite. A wide range of mineral assemblages is represented.

Most of the Precambrian outcrops consist of gently tilted sediments of the Kimberley Basin to the west and the Victoria River Basin to the east. Outliers crop out in the Carr Boyd Ranges, south of Kununurra, and in the Osmond and Albert Edward Ranges farther south towards Halls Creek. The bulk of the Precambrian sediments comprise clean well sorted quartz sandstone, subordinate siltstone and shale, and minor acid and basic volcanics and carbonate rocks. Widespread basic intrusives occur in the west.

UPPER DEVONIAN

The Upper Devonian is represented by 5,000 feet of outcropping Frasnian shallow-water quartz sandstone, conglomerate, and carbonate rocks (Cockatoo Formation), overlain by 1,000 feet of outcropping Famennian carbonate rocks of a reef complex (Ningbing Limestone), and 1,100 feet of equivalent outcropping Famennian lagoonal carbonate rocks and sandstone (Buttons Beds) deposited nearer the land to the south and southeast. At least 2,300 feet of equivalent Famennian and possibly Frasnian deeper-water dark siltstone and shale, with minor quartz sandstone (lower part of Bonaparte Beds), are known in well sections only. The quartz sandstone, conglomerate, and carbonate rock were deposited on a shallow-water platform, and the siltstone and shale in a slightly deeper depression or basin. Accordingly, we have distinguished three main facies and corresponding depositional provinces: the platform conglomeratic facies and province, the platform carbonate facies and province, and the basinal shale facies and province. The distribution of the facies and provinces is shown diagrammatically in Figure 10. The terms 'platform' and 'basin' have the meaning given them by Dunbar & Rodgers (1957, pp. 308-9). According to these authors, the 'stable platforms' of the continents may contain 'persistently negative' areas, which 'form distinct basins within the platform'.

Early in the Frasnian the region, which was underlain by Precambrian, Cambrian, and Ordovician sediments (mainly quartz sandstone) and minor volcanics, was cut into blocks by movements along ancient faults. Continued movement along these and other faults throughout the rest of the Upper Devonian was the dominant influence over contemporaneous erosion and deposition.

The southeastern margin of the basin was marked in the early Frasnian by a zone of faults with downward displacement to the northwest. The faults were apparently normal, but had an undetermined wrench component. Wedges of quartzite-boulder conglomerate (Ragged Range Member) were deposited at the foot of the fault scarps, but within a few miles the conglomerate passed laterally into coarse cross-bedded quartz sandstone (Kellys Knob Member). How much of the basal quartz sandstone and marginal conglomerate is marine is not known; rare macrofossils (chiefly pelecypods and gastropods) have been found, even in the coarse conglomerate, but it is uncertain whether these indicate continuous marine deposition or intermittent marine incursions over a low-lying coast. Certainly, the ubiquitous cross-bedding, ripple marks, lineation, and thorough winnowing in the Kellys Knob Member indicate deposition in fairly shallow turbulent water. One thousand feet of this member was deposited under uniform conditions, and was followed by the deposition of a mixture of quartz sand and carbonate rocks. Near the southeastern boundary fault, this unit consists of glauconitic sandstone with minor carbonate sediments (Kununurra and Abney Members); there is a gradual lateral transition into the Hargreaves Member, and the equivalent unit 70 miles to the northwest, near the mouth of Cambridge Gulf, is a reef (Westwood Member), which is represented in outcrop by fore-reef only. The fore-reef is a stromatolite breccia with a matrix of schizophyte algae.

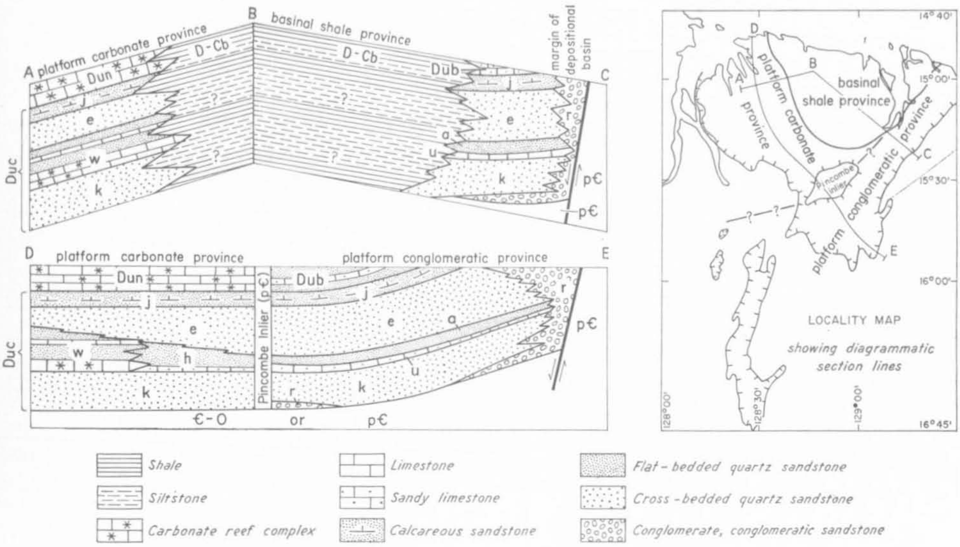


Figure 10. Diagrammatic relationships of Upper Devonian stratigraphical units

D-Cb Bonaparte Beds: dark siltstone and shale, minor sandstone
Dun Ningbing Limestone: carbonate reef complex
Dub Buttons Beds: silty limestone, minor shale, sandstone
Duc Cockatoo Formation
j Jeremiah Member: interbedded sandstone, siltstone and carbonates
e Cecil Sandstone Member: quartz sandstone, cross-bedded
w Westwood Member: sandy carbonate, including incipient reef, sandstone
h Hargreaves Member: sandy carbonate, sandstone, marl
a Abney Sandstone Member: red thin-bedded sandstone
u Kununurra Member: sandy carbonate, sandstone
k Kellys Knob Sandstone Member: quartz sandstone, cross-bedded
r Ragged Range Conglomerate Member: conglomerate, pebbly sandstone
C-O Cambrian-Ordovician
pC Precambrian

NOTE: Diagram not to scale.

Probably as a result of renewed faulting, deposition of conglomeratic sandstone along the southeastern boundary fault was resumed, and cross-bedded quartz sandstone was deposited elsewhere. About 2,000 feet of Cecil Member accumulated in a very shallow sea, or along a low-lying coast, or in a combination of both. Towards the end of the Frasnian, the effect of the faulting waned and, above a sandy carbonate sequence (Jeremiah Member), a Famennian carbonate reef complex was deposited, presumably on a slowly sinking block. The reef complex (Ningbing Limestone) consists of 1,000 feet of a well exposed back-reef and a narrow reef, and poorly exposed inter-reef and fore-reef. Behind the reef complex, nearer the land, 1,100 feet of interbedded impure carbonate sediment and sandstone (Buttons Beds) was deposited in a lagoon. At least 2,300 feet of deeper-water dark siltstone and shale (lower part of Bonaparte Beds) was deposited contemporaneously, and the change from shallow-water to deeper-water deposition took place over a narrow zone less than 10 miles wide near the Bonaparte No. 1 well. The zone was probably controlled by hinge-faulting.

The Upper Devonian sediments in the western part of the basin were tilted, faulted, uplifted, and eroded during the Lower Carboniferous. In the east and south, the main period of faulting was much later, in the Permian or Mesozoic.

FRASNIAN: COCKATOO FORMATION

The Frasnian Cockatoo Formation comprises about 5,000 feet of quartz sandstone, conglomerate, limestone, and dolomite that crop out over large areas in the Bonaparte Gulf Basin and in its outliers. The formation uncomformably overlies the Precambrian and Cambrian-Ordovician sequences, and is conformably overlain, above transition beds, by the Ningbing Limestone or Buttons Beds. The proportions of conglomerate, quartz sandstone, and limestone or dolomite vary considerably, both vertically and laterally, and the name has therefore been revised from Cockatoo Sandstone to Cockatoo Formation.

The first published reference to outcrops of the Cockatoo Formation was by Wade (1924, p. 33). He noted the conspicuous false bedding and the ease with which it crumbles to sand in the Cockatoo Spring area. He also noted the similarity of the formation in the Cockatoo Spring area to other outcrops at Mount Glass and Mount Buchanan in the Hardman Basin which were mapped as sandstones, probably old dune deposits, of unknown age. The conglomerate north of Cockatoo Springs was also noted.

Matheson & Teichert (1948, p. 82) introduced the name Cockatoo Series, and showed its distribution between Cockatoo Spring and Martin Bluff and near Buttons Crossing. They gave its minimum thickness as 4,000 feet in the Cockatoo Spring area, found plant fossils, and dated it as Upper Devonian.

Reeves (1951) reduced the thickness of the Cockatoo Series to 3,000 feet because, as he explained in an earlier unpublished report, he regarded the core of Mount Cecil as Precambrian. It was in this paper that the name Bonaparte Gulf Basin was introduced.

Noakes et al. (1962, pp. 94-5) revised the name to Cockatoo Sandstone, and introduced the name Onslow Beds for the Upper Devonian sandstone and limestone in the Onslow Hills approximately equivalent to the Cockatoo Sandstone, but did not describe it adequately.

Traves (1955) extended the known distribution of the Cockatoo Sandstone to the west and northwest of Ningbing and discovered the Dillon Spring outlier. He recorded numerous fossils, mainly pelecypods, from several localities. In the Pretlove Hills and along the eastern edge of the basin, rocks which are now recognized as Cockatoo Formation were mapped as Cambrian and Permian, and the Ragged Range Conglomerate was also dated as Cambrian. Traves followed Reeves in regarding the core of Mount Cecil as Precambrian, despite the fossils he found nearby.

E. P. Utting's (pers. comm.) main discovery in the Cockatoo Formation was the richly fossiliferous exposure at Westwood Creek.

Veevers et al. (1964) summarized the results of mapping in 1963. Many of the new observations reported were independently made by Australian Aquitaine Petroleum (Guillaume, 1966). The new information concerned the Upper Devonian age of the Ragged Range Conglomerate, the sandstone and dolomite of the Pretlove Hills, and the outcrops in the Nigli Gap area, and the presence of thick fossiliferous interbedded limestone and sandstone at Westwood Creek. Jones & Druce (1966) have listed the conodonts from Westwood Creek, which indicate a Frasnian age.

Summary Description and Relationship of Members

The chief lithological variations in the Cockatoo Formation have been mapped as eight members, seven of them new. The relationship between the members is shown diagrammatically in Figure 10.

The *Ragged Range Conglomerate Member* is a basal wedge of boulder conglomerate and red-brown lithic quartz sandstone, at least 1,000 feet thick, that was deposited along the eastern margin of the basin, and in front of the southern part of the Pincombe Inlier.

The *Kellys Knob Sandstone Member* is a tabular body of cross-bedded quartz sandstone, at least 1,000 feet thick, that extends over both parts of the platform province. In the conglomeratic province it is commonly pebbly, and is conglomeratic at the margin itself.

The *Kununurra Member* is a sheet of fossiliferous fine-grained glauconitic quartz sandstone and dolomite, 300 feet thick, which is known from the conglomeratic province only. Its dolomitic content increases with its distance from the margin of the basin.

The *Abney Sandstone Member* is a sheet of thin-bedded red-brown quartz sandstone, 330 feet thick, which is also known from the conglomeratic province only. It is pebbly near the margin of the basin.

The *Hargreaves Member* is a tabular body of sandstone, dolomite, and marl in the southwestern part of the carbonate province. It is probably about 2,000 feet thick. Part or all of it is laterally equivalent to the Kununurra and Abney Members, and to the Westwood Member.

The *Westwood Member* is a tabular body of quartz sandstone and limestone which is known only in the northwestern part of the carbonate province. It is probably up to 2,000 feet thick. The Westwood Member is the extreme type of carbonate development of the Cockatoo Formation which culminated in the formation of a reef. It is equivalent to the Kununurra, Abney, and Hargreaves Members, and probably to the lower part of the Cecil Member.

The *Cecil Sandstone Member* is a tabular body of cross-bedded quartz sandstone that extends over the platform province. It is at least 2,000 feet thick. It is similar to the Kellys Knob Member, but is thicker.

The *Jeremiah Member* is a sheet of sandy dolomite, at least 360 feet thick, that extends over the platform province. It links the rest of the Cockatoo Formation with the overlying Ningbing Limestone and Buttons Beds.

The lower part of the *Bonaparte Beds,* which are not included in the Cockatoo Formation but are possibly equivalent to part or all of it, comprise thick dark siltstone with minor sandstone and shale, and are known only in the subsurface of the shale province. The age of the lowermost part of the beds penetrated in the Kulshill No. 1 well is not precisely known, but the beds are Famennian or older, and possibly Frasnian or even Middle Devonian.

Some of these ideas are summarized in Figure 10.

Detailed Description of Members

Platform Conglomeratic Province

Martin Bluff/Kununurra Area (Fig. 11)

The Martin Bluff/Kununurra area contains the type localities of four members. The outcrops are the westernmost of the Burt Range Syncline, on which the Mount Cecil Dome and Martin Bluff Monocline have been superimposed.

Ragged Range Conglomerate Member

The type Ragged Range Conglomerate Member in the Ragged Range is discussed on page 26. In the Martin Bluff area, the Ragged Range Member is a poorly exposed lens of pebble to boulder conglomerate and red-brown sandstone that unconformably overlies the Cambrian Antrim Plateau Volcanics and is conformably overlain by the Kellys Knob Member. To the east and south, the Ragged Range Member wedges out and the Kellys Knob Member rests directly on the Antrim Plateau Volcanics.

In the Ragged Range Member, the thickness and proportion of conglomerate and sandstone varies considerably (Fig. 12). In section 412, which is incomplete, the Ragged Range Member consists of an estimated 330 feet of thin-bedded, cross-bedded, medium to coarse sandstone and 15 feet of boulder conglomerate (Pl. 2, fig. 1), first described by Matheson & Teichert (1948, p. 83). Most fragments in the conglomerate are rounded boulders of metaquartzite, and the biggest are blocks, up to 3 feet across, of basalt (Pl. 2, fig. 2); a few pebbles of other igneous rocks were also found. Two miles to the east, the Ragged Range Member is slightly thinner than in section 412, and in the washaways on the western flank of Martin Bluff (loc. 86/1) the member consists of roughly equal amounts of basalt wash and laminated red to chocolate fine sandstone. The wash consists of basalt detritus up to the size of boulders, with rare pebbles of metaquartzite and vein quartz. A little over 2 miles farther east, at locality 411/2, the Ragged Range Member is only 55 feet thick, and consists predominantly of cross-bedded red-brown medium sandstone, with only 5 feet of conglomerate. A short distance to the east of this locality, the Ragged Range Member probably wedges out, as it does between Church Steeple Peak and Kellys Knob.

Apart from the Martin Bluff/Kununurra area and the type area, outcrops of the Ragged Range Member are known only along the southeast margin of the basin (Fig. 13).

The distinctive characteristics of the Ragged Range Member are its cobble and boulder conglomerate, and the red colour of its sandstone.

Kellys Knob Sandstone Member (new name)

The Kellys Knob Sandstone Member is here defined as the tabular body of yellow to white quartz sandstone between the Antrim Plateau Volcanics or Ragged Range Conglomerate Member and the Kununurra or Abney Members in the

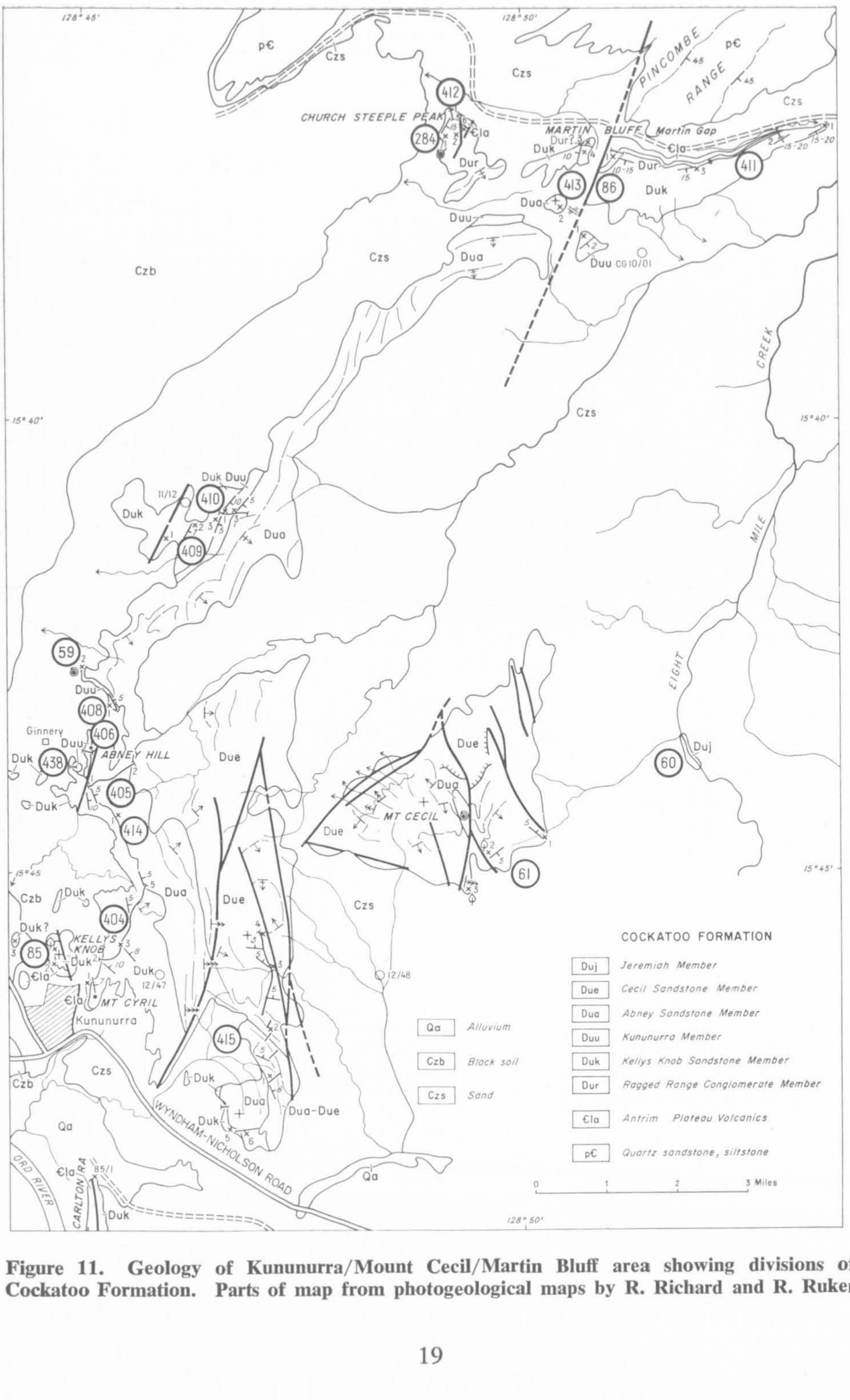


Figure 11. Geology of Kununurra/Mount Cecil/Martin Bluff area showing divisions of Cockatoo Formation. Parts of map from photogeological maps by R. Richard and R. Ruker

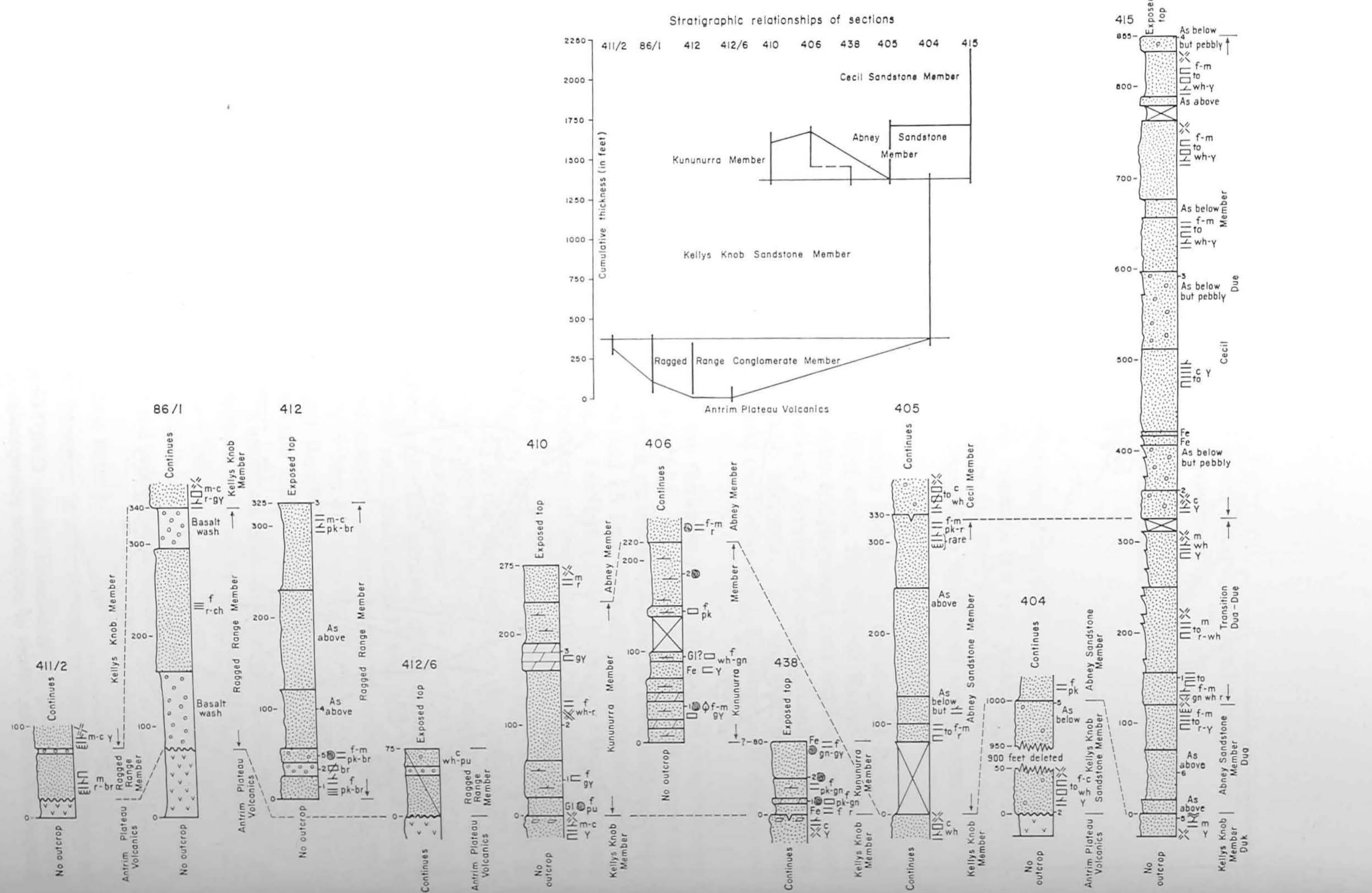


Figure 12. Columnar sections and stratigraphic relationships of Cockatoo Formation, Kununurra area. (See Fig. 11 for location)

Kununurra/Martin Bluff area. The type section is section 404, east of Kellys Knob, at latitude 15°46′S., longitude 128°45′E. In the type section, the Kellys Knob Member unconformably overlies the Antrim Plateau Volcanics, and is paraconformably overlain by the Abney Sandstone Member. In Martin Bluff (Pl. 3), the Kellys Knob Member overlies the Ragged Range Member, and between Abney Hill and Martin Bluff the unit is conformably overlain by the Kununurra Member. Except for increasing amounts of pebbles and boulders near the margin of the basin, where it seems to pass laterally into the Ragged Range Member, the Kellys Knob Member is a remarkably uniform yellow to white quartz sandstone.

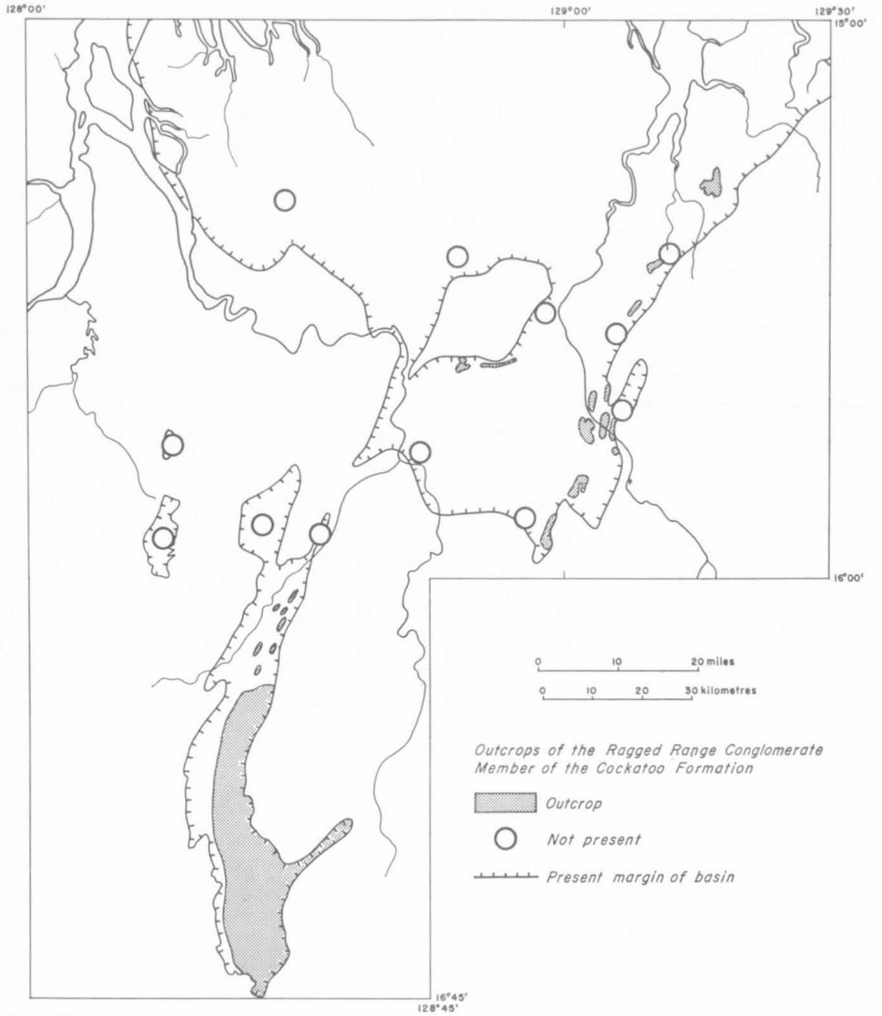


Figure 13. Ragged Range Conglomerate Member, Cockatoo Formation

In the type section (Fig. 12), the Kellys Knob Member consists of 1,000 feet of uniform white to yellow friable quartz sandstone, with rare pebbles. The beds are deeply jointed, medium to thick-bedded, cross-bedded, and fine to coarse-grained. On the air-photographs, the Kellys Knob Member has a rough pattern of regular close vertical joints and a light tone. The sandstone is weakly cemented by overgrowths around the quartz grains, but when the thin weathered skin of the rock is broken with a hammer, it disintegrates into sand. The outcrops are partly concealed by loose sandy eluvium, and are deeply incised along joints. The joints cut the beds into 'bricks', which, together with the deep joints, give the outcrops a castellated appearance. The characteristic cross-bedding in the Kellys Knob Member has been illustrated by Matheson & Teichert (1948, fig. 9) and Traves (1955, fig. 25). Ripple marks and contorted stratification are less common. An unusual feature is the presence of intraformational breccia composed of angular fragments of thin-bedded sandstone embedded in similar sandstone, at the top of the Kellys Knob Member, in sections 438 and 410 (Fig. 12). These and other sedimentary structures will be described in a forthcoming publication by Veevers (BMR Bull. 109, in prep.).

The only fossil found in the type locality is the plant *Leptophloeum,* which occurs about 200 feet above the base of Kellys Knob (J. N. Casey, BMR, pers. comm.). Indeterminate pelecypods have been found in the Alpha Hill and Matheson Ridge areas.

The Kellys Knob Member can be distinguished from most other members of the Cockatoo Formation by its uniform quartz sandstone lithology, jointing, and cross-bedding; from the Cecil Sandstone Member it can be distinguished only by its stratigraphic position.

Kununurra Member (new name)

The Kununurra Member is here defined as the lenticular body of varicoloured fine micaceous quartz sandstone, dolomitic sandstone, and dolomite between the Kellys Knob and Abney Members in the area between Abney Hill and Martin Bluff. Section 410, which is 235 feet thick, is designated as the type section. The co-ordinates of the base of the section are latitude 15°41′S., longitude 128°46′E. On the air-photographs, the Kununurra Member is a uniform grey with only few traces of bedding, and is indistinguishable from the overlying Abney Member.

South of Abney Hill, the Kununurra Member wedges out and the Abney Member rests on the Kellys Knob Member (Pl. 4, fig. 1). The change is rapid, and in section 438-406, which is 220 feet thick, the unit wedges out entirely near a fault a quarter of a mile to the south. The fault is probably a scissor fault; the Kununurra Member was probably deposited on the downthrown block, and the upthrown block, which was covered by the Kellys Knob Member, was an area of non-deposition.

In the conglomeratic province, the Kununurra Member is the oldest of the abundantly fossiliferous members, and in the type area conodonts, pelecypods, crinoid ossicles, trace fossils, and plants (*Leptophloeum*) have been found.

The Kununurra Member lies between white and red sandstone, and is distinguished by its finer grain, grey or green colour, and the presence of beds of dolomite, and of fossils.

Abney Sandstone Member (new name)

The Abney Sandstone Member is here defined as the tabular body of red thin-bedded fine to medium-grained quartz sandstone above the Kellys Knob Member and below the Cecil Sandstone Member south of Abney Hill. In Abney Hill

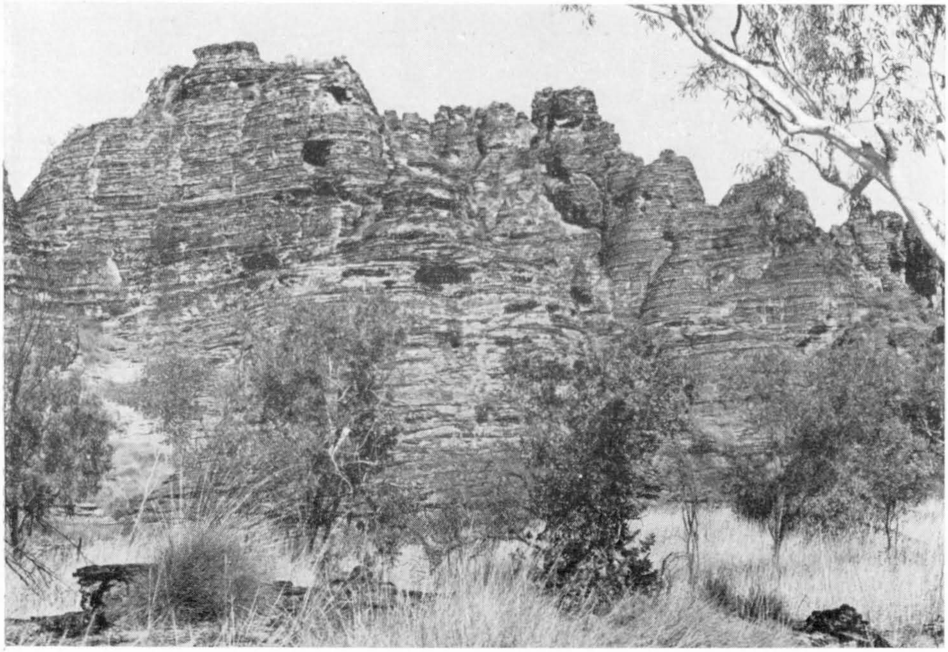


Plate 7, Figure 1. Flat-bedded and occasional cross-bedded quartz sandstone of the Kellys Knob Member (Traves' Nigli Gap Sandstone) in the southern wall of Nigli Gap. cf. fig. 29 of Traves (1955)

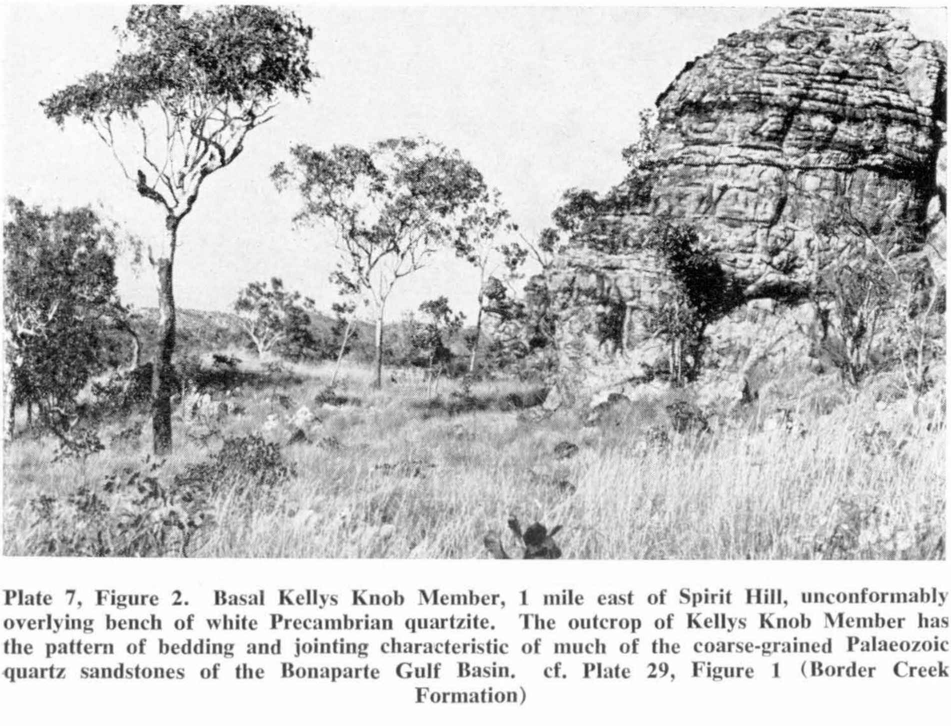


Plate 7, Figure 2. Basal Kellys Knob Member, 1 mile east of Spirit Hill, unconformably overlying bench of white Precambrian quartzite. The outcrop of Kellys Knob Member has the pattern of bedding and jointing characteristic of much of the coarse-grained Palaeozoic quartz sandstones of the Bonaparte Gulf Basin. cf. Plate 29, Figure 1 (Border Creek Formation)

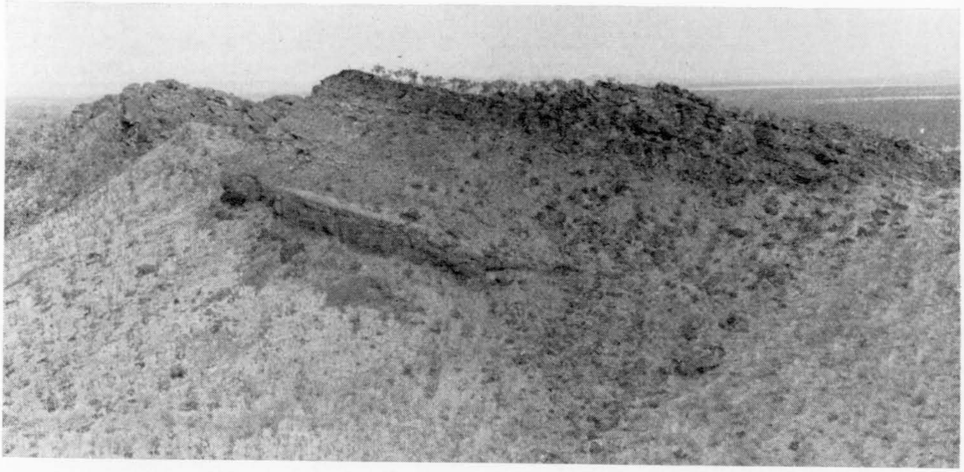


Plate 8, Figure 1. Looking along the strike (southwest) at Alpha Hill (locality 134) (Fig. 18). The prominent ledge is a coarse red conglomerate, and it is overlain by alternating light and dark sandstone. These sediments, interdigitations of the Ragged Range and Kellys Knob Members, unconformably overlie the Antrim Plateau Volcanics

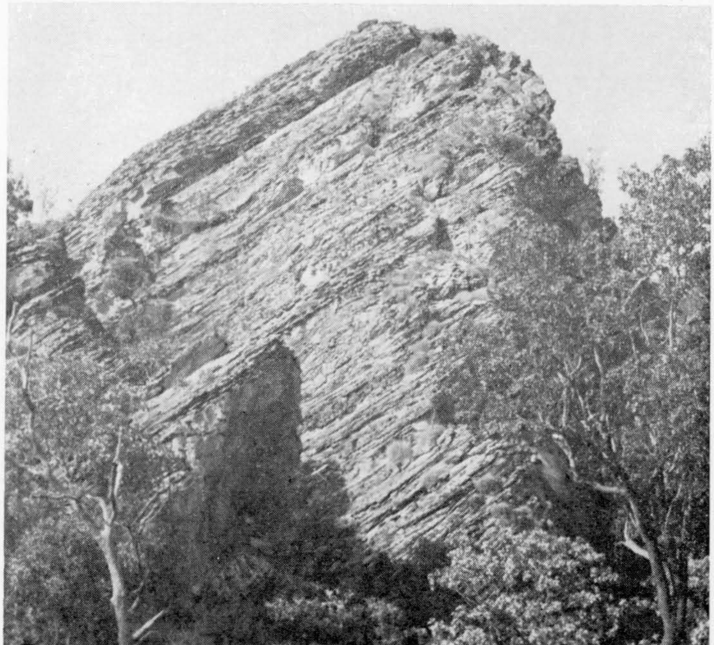


Plate 8, Figure 2. Northeast-dipping quartz sandstone of the Cockatoo Formation near the track crossing at Redbank Creek in the Pretlove Hills, 15 miles west of Point Spring

Plate 9, Figure 1. Westwood Member. Looking north-northeast at locality 459. Conical outcrop of fore-reef(?) limestone at edge of tidal mud flat, and ribs of limestone between softer sandstone interbeds. The parallel lines on the tidal flats are vehicle tracks

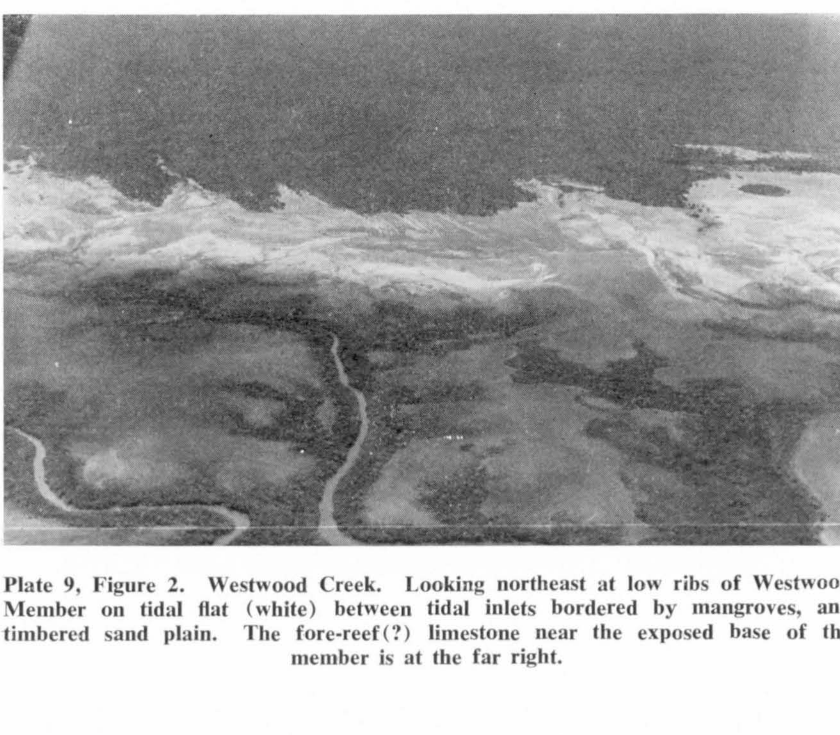


Plate 9, Figure 2. Westwood Creek. Looking northeast at low ribs of Westwood Member on tidal flat (white) between tidal inlets bordered by mangroves, and timbered sand plain. The fore-reef(?) limestone near the exposed base of the member is at the far right.

Plate 10, Figure 1. Conical outcrop of fore-reef(?) limestone at locality 459-15 in the Westwood Member. The main mass of the cone is a breccia of stromatolite fragments embedded in a matrix of blue-green alpha *(Renalcis)*. The hammer is 12 inches (30 cm) long

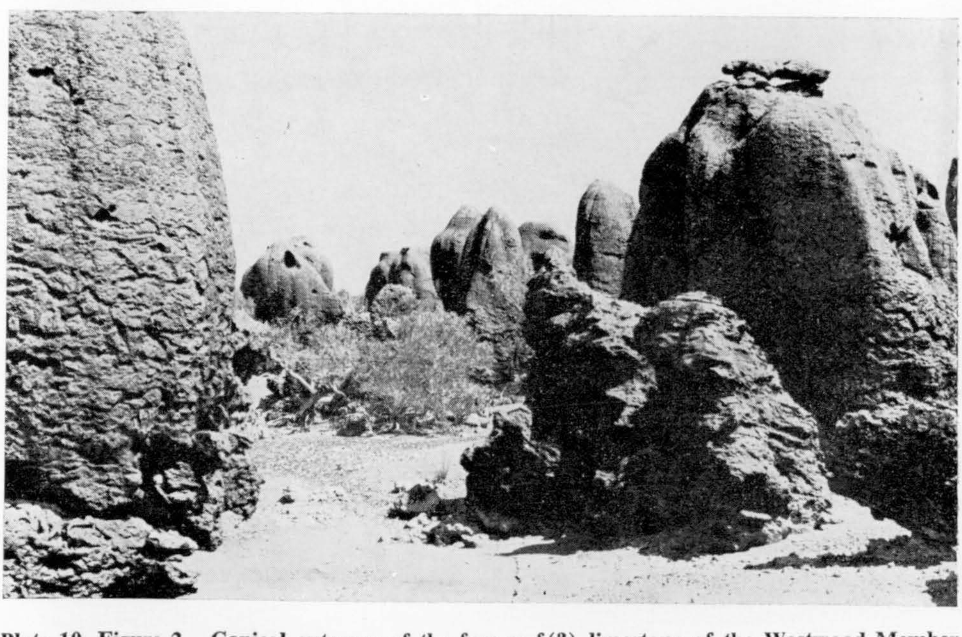


Plate 10, Figure 2. Conical outcrops of the fore-reef(?) limestone of the Westwood Member at locality 459. These outcrops are about 12 feet high

Plate 11, Figure 1. Pelecypod shell bank at locality 459-2 in the Westwood Member. The pelecypod is identified by J. M. Dickins (pers. comm.) as *Paracyclas* sp. The ink marker is 4 inches (10 cm) long

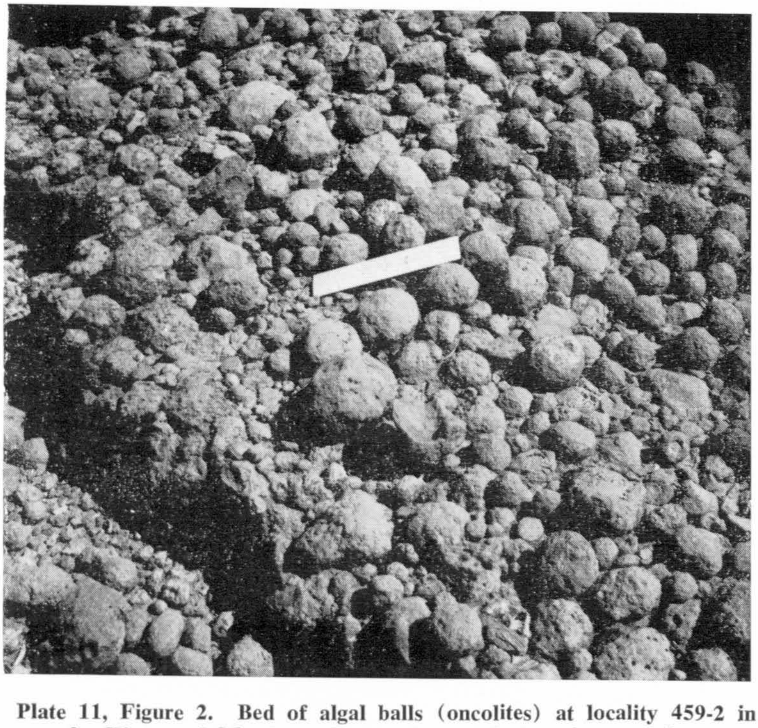


Plate 11, Figure 2. Bed of algal balls (oncolites) at locality 459-2 in the Westwood Member. The scale is 6 inches (15 cm) long

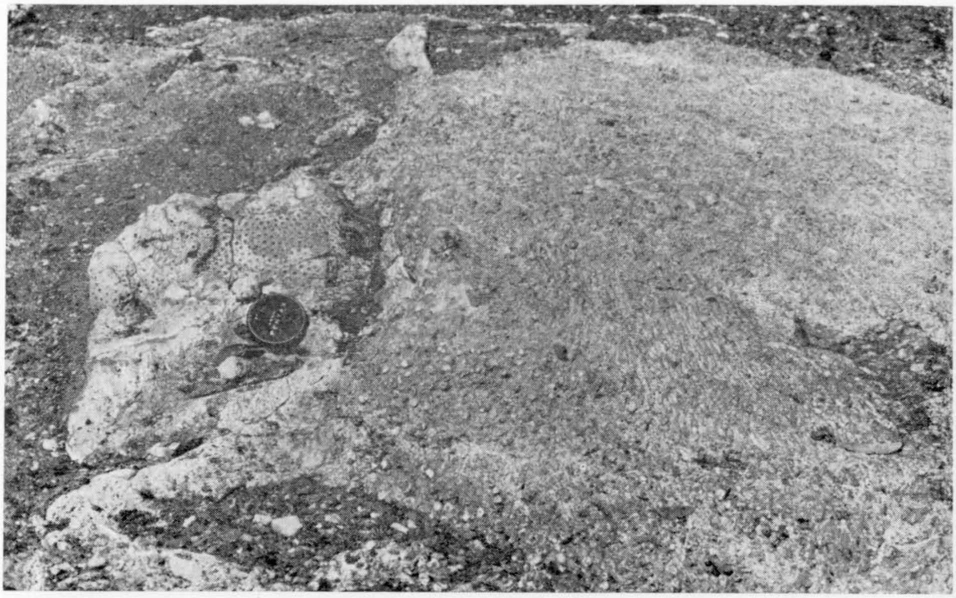


Plate 12, Figure 1. Compound corals in the Westwood Member. Large colonies of *Hexagonaria* (left) and *Disphyllum* at locality 12-2. The lens cover is 2 inches (5 cm) across

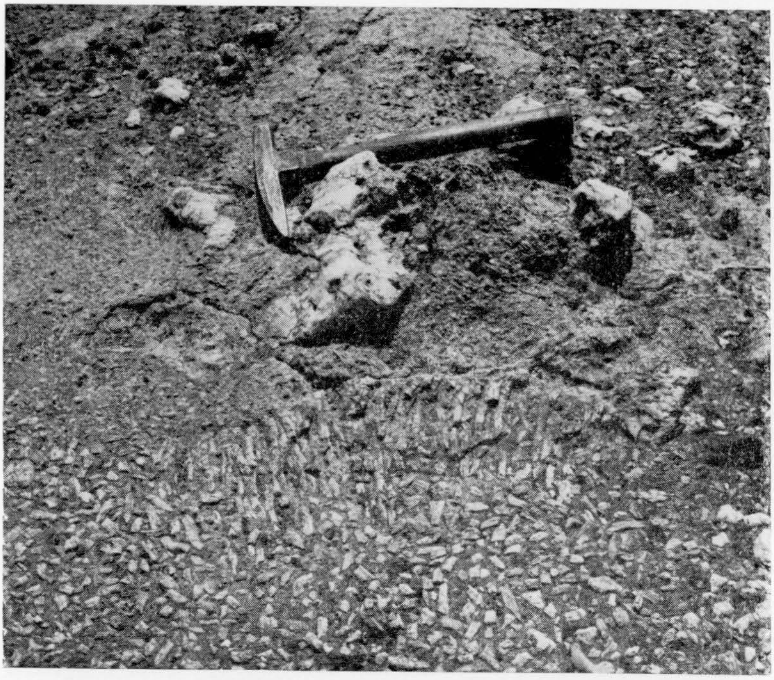


Plate 12, Figure 2. Coral colonies in the Westwood Member. Looking down on horizontal surface of *Disphyllum* (lower part of photo), and *Alveolites*, and probable stromatoporoids (white). The hammer is 12 inches (30 cm) long

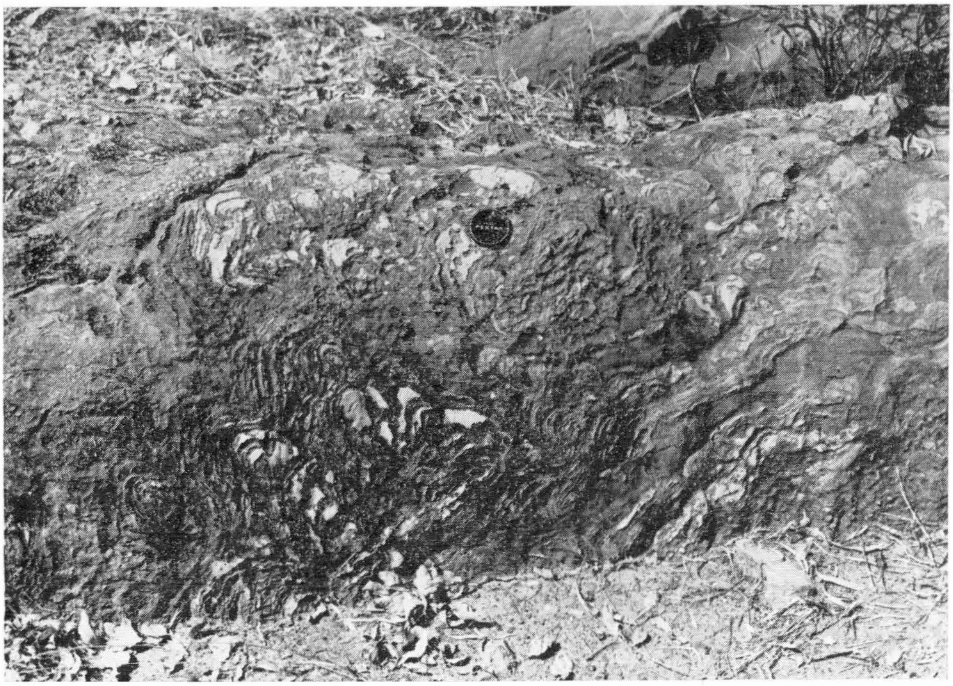


Plate 13. Intergrown laminar stromatoporoid (white) and stromatolite in the Westwood Member at locality 460. The lens cover is 2 inches (5 cm) across

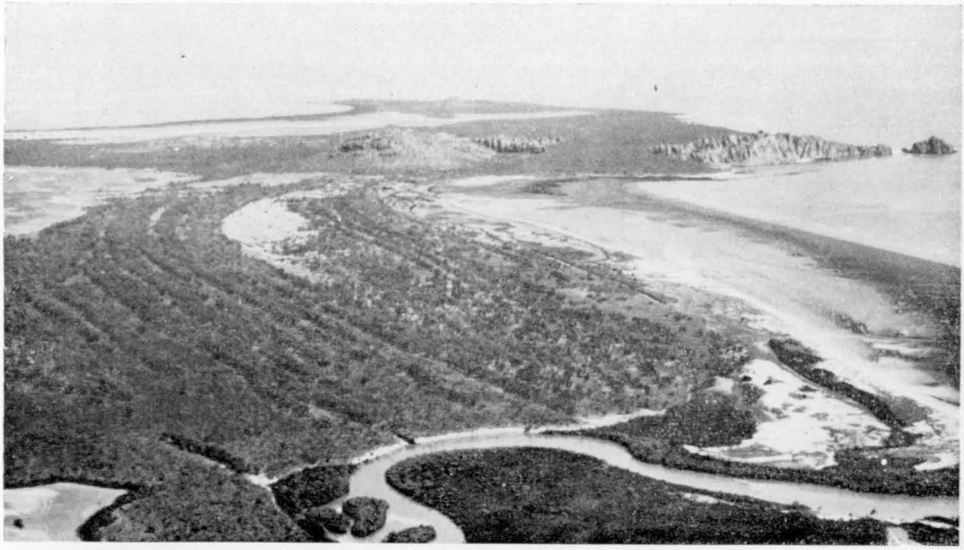


Plate 14, Figure 1. Looking west at Cape Domett. Parallel beach ridges between tidal inlet (Westwood Creek) and hill (Shakespeare Hill). Cliffs at Cockatoo Formation on right. The low cone in the background is Cone Hill

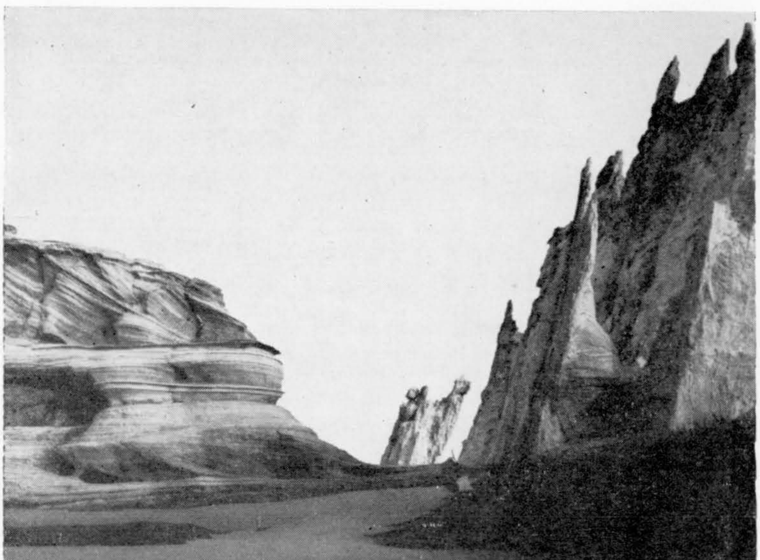


Plate 14, Figure 2. Looking at a south-southeast fault zone through friable crossbedded quartz sandstone of the Cockatoo Formation, probably Kellys Knob Member, ½ mile south of Cape Domett. The sandstone is silicified in the fault zone but is unaffected on either side itself, the Abney Sandstone rests on the Kununurra Member. The Kununurra Member wedges out south of Abney Hill, and the boundary between the Kellys Knob Member and the Abney Member represents a paraconformity or disconformity.

Section 405, which is 330 feet thick, is the type section of the Abney Member (Fig. 12). The co-ordinates of the base of the section are latitude 15°44′S., longitude 128°45′E. On the air-photographs, the Abney Member is a uniform grey showing faint bedding, and is indistinguishable from the underlying Kununurra Member. In section 415, 2½ miles east-southeast of Kununurra, the Abney Member passes upwards into the Cecil Member through 200 feet of transitional beds. In section 405 the boundary between the Abney and Cecil Members is an erosional surface, with trough cross-beds in the Cecil Member cutting 2 feet down into the top of the Abney Member.

The Abney Member in the core of the Mount Cecil Dome contains pelecypods, which were discovered by Traves (1955, loc. 12). The brachiopods at the top of section 406 are the only other fossils known from the Member.

The diagnostic features of the Abney Member are its red colour and uniform thin to medium-bedding.

Cecil Sandstone Member (new name)

The Cecil Sandstone Member is here defined as the tabular body of white to yellow quartz sandstone resting on the Abney Member in the Kununurra/Mount Cecil area. The type section, which is incomplete, is section 415, 2½ miles east of Kununurra (Fig. 12). The co-ordinates of the base of the section are latitude 15°47′S., longitude 128°47′E. In the type locality, parts of the Cecil Member are pebbly, and the pebbly content increases eastward towards the margin of the basin. Elsewhere, the Cecil Member, like the Kellys Knob Member, is a uniform quartz sandstone without pebbles. The Cecil Member is similar to the Kellys Knob Member, but it is thicker and exceeds 1,800 feet in the type section of the Cockatoo Formation.

At Mount Cecil, the Cecil Member is silicified, probably as the result of intense faulting, and has an unusual pattern on the air-photographs. Elsewhere, the Cecil and Kellys Knob Members are indistinguishable by air-photo interpretation, and their identification depends entirely on their stratigraphical position.

The only fossil known in the type locality is the plant *Leptophloeum* from Mount Cecil, which was discovered by Matheson & Teichert (1948). In other areas, fish plates have also been found.

The top of the Cecil Member is not exposed here or elsewhere, so that its detailed relationship with the overlying poorly exposed Jeremiah Member is not known.

Matheson Ridge Area (Fig. 14; Pl. 4, fig. 2; Pl. 5, fig. 1)

Matheson Ridge includes the type locality of the Cockatoo Formation, and is situated on the western limb of a north-pitching syncline.

Type Section of the Cockatoo Formation

Matheson & Teichert (1948, p. 82) designated the area northwest of Cockatoo Spring as the type area, and we here designate section 28-29-30-58 (Fig. 15) across Matheson Ridge as the type section. In this section, the Cockatoo Forma-

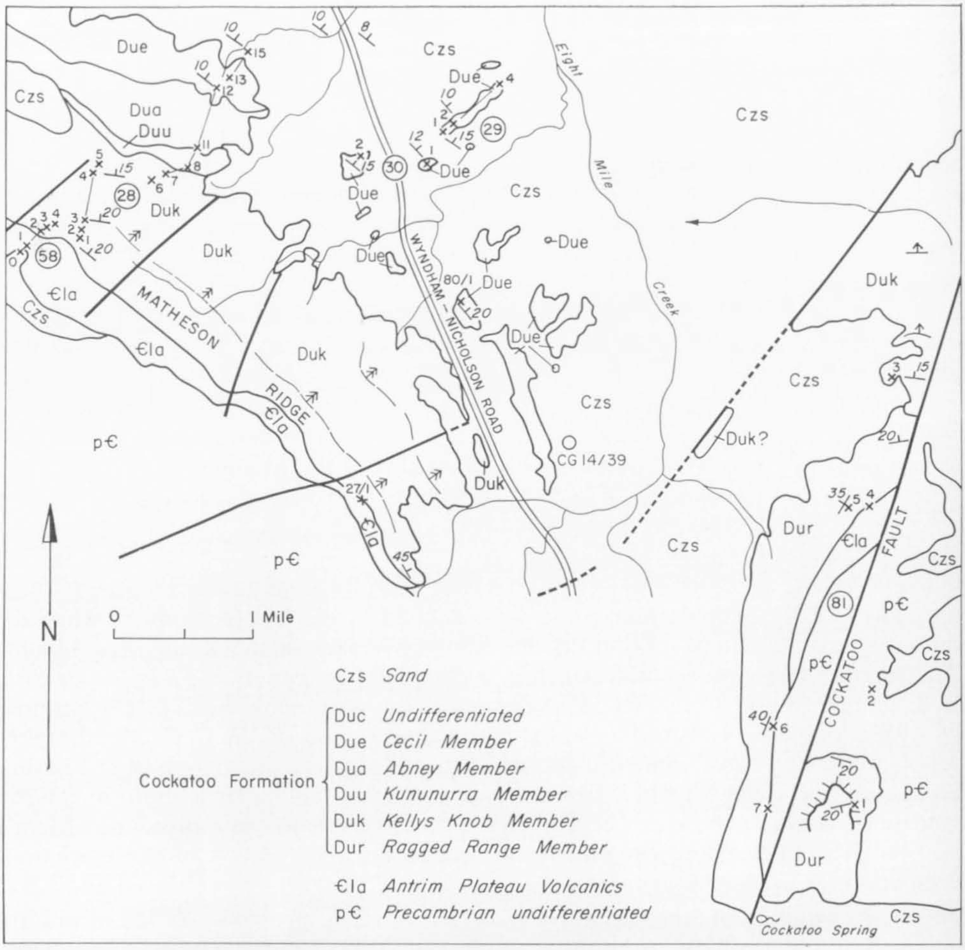


Figure 14. Geology of Matheson Ridge/Cockatoo Spring area. Modified from photogeological map by R. Ruker

tion rests unconformably on the Antrim Plateau Volcanics, and its top is exposed. The section is about 3,500 feet thick; it differs from the section in the Kununurra/Martin Bluff area in the absence of the Ragged Range Member, and in being thicker except for the Kununurra Member. With the exception of the Kununurra Member, the type section contains more pebbles and cobbles, which are locally concentrated in the Kellys Knob Member in beds of conglomerate. Also, the uppermost 200 feet of the Kellys Knob Member is red.

The Kununurra Member generally resembles the type section, but is only half as thick and contains only one thin bed of dolomite. Pelecypods, brachiopods, and trace fossils are common. The Abney and Cecil Members here also correspond to the type section, except that they are thicker and contain abundant pebbles, cobbles, and boulders (Pl. 5, fig. 2). The Cecil Member is incomplete, but its measured thickness of 1,820 feet is the thickest known exposure. The air-photo patterns are the same as in the Kununurra area, except for a visible difference between the Kununurra and Abney Members.

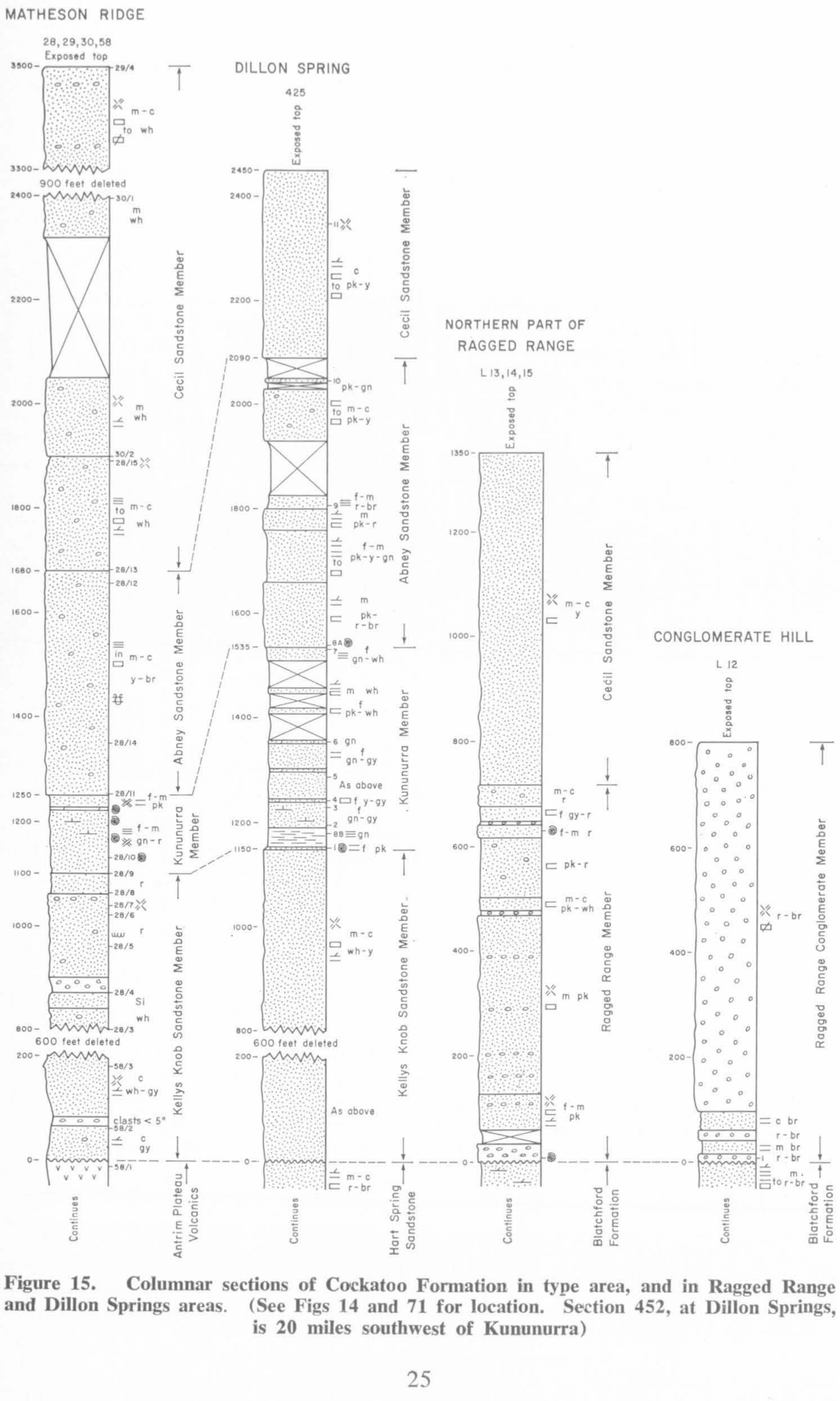


Figure 15. Columnar sections of Cockatoo Formation in type area, and in Ragged Range and Dillon Springs areas. (See Figs 14 and 71 for location. Section 452, at Dillon Springs, is 20 miles southwest of Kununurra)

In the Cockatoo Spring area (Fig. 14; Pl. 6), the Ragged Range Member rests unconformably on the Antrim Plateau Volcanics and Precambrian sheared metaquartzite to the west of the Cockatoo Fault, and on Precambrian metamorphics to the east. At locality 81/1 on the eastern side (Matheson & Teichert, 1948, p. 82; Traves, 1955, p. 72), the Ragged Range Member is exposed in a prominent cliffed hill, 650 feet high. It consists of rounded pebbles and boulders, up to 2 feet across, of metaquartzite and rare weathered igneous fragments in a sparse sandstone matrix. The conglomerate contains lenses, up to 6 inches thick, of friable brown lithic quartz sandstone with angular pebbles of slate. The conglomerate is thick-bedded and deeply jointed, and the estimated minimum thickness is 1,000 feet. The section is virtually identical with the type section at Conglomerate Hill (described below), as noted by Matheson & Teichert (1948, p. 85).

On the other side of the fault, the Ragged Range Member dips at up to 40° in a dome cut by the Cockatoo Fault (Matheson & Teichert, 1948, fig. 1). On the air-photographs, the Ragged Range Member has an even dark grey tone. At locality 81/7, three-quarters of a mile north of Cockatoo Spring, steeply dipping closely jointed Precambrian metaquartzite is overlain by a basal breccia of angular fragments of the underlying metaquartzite and siliceous siltstone set in a lithic quartz sandstone matrix containing lenses of pink quartz sandstone. The nearest boulders of the conglomerate lie on the surface a few paces to the west. The breccia may represent the base of the Ragged Range Member at this locality or it may be a later superficial deposit. No consolidated superficial deposits of this kind are known in the area, and as the pink quartz sandstone interbedded with the breccia resembles the sandstone interbedded with the conglomerate, we regard the breccia as the local base of the Ragged Range Member.

The Ragged Range Member west of the Cockatoo Fault consists almost entirely of conglomerate with cobbles and boulders of metaquartzite and rare interbedded sandstone; the estimated minimum thickness is 700 feet. Four miles north-northeast of Cockatoo Spring, the Ragged Range Member is overlain, apparently conformably, by a jointed cross-bedded white sandstone identified as the Kellys Knob Member. Three miles to the west, in Matheson Ridge, the Kellys Knob Member rests directly on the Antrim Plateau Volcanics; its absence demonstrates the rapid thinning of the Ragged Range Member away from the margin of the basin.

Ragged Range, Dillon Spring, and Mount Rob Areas (The Outliers)

The same lateral change in the Cockatoo Formation from the Cockatoo Spring area through Matheson Ridge to Kununurra is found between Ragged Range, Dillon Spring, and Mount Rob.

Ragged Range Conglomerate Member

The Ragged Range Conglomerate of Traves (1955, pp. 46-7) was first regarded as a Cambrian formation, but was later found to be Devonian (Veevers et al., 1964; Kaulback & Veevers, 1968). It is here designated as a member of the Cockatoo Formation. Two columnar sections of the Ragged Range Member are shown in Figure 15, and the field relationships are described in Kaulback & Veevers (1968).

The section at Conglomerate Hill (Fig. 15, section L12), where the most conglomeratic development of the Ragged Range Member is found, is here designated the type section. It comprises 800 feet of deeply jointed very thick-bedded red-brown cobble to boulder conglomerate with minor brown quartz sandstone. In the northern part of the Ragged Range (sections L13-15), the section is divisible into two parts: pink to red-brown conglomerate and conglomeratic sandstone in the lower half, and jointed yellow quartz sandstone in the upper half. Only the lower half of the section is the Ragged Range Member; the upper half has been assigned to the Cecil Member, because of the absence of conglomerate and red sandstone which are characteristic of the Ragged Range Member. The exposure in section L13-15 has many points in common with the Kellys Knob Member in the Matheson Ridge section, but the predominant pink and red colour indicates that it belongs to the Ragged Range Member. Indeterminate pelecypods and gastropods are found in conglomerate at the base, and pelecypods in red sandstone near the top. The only other fossils recorded are indeterminate pelecypods found immediately above the conglomerate bed at Church Steeple Peak (section 412), and *Leptophloeum* at the Ochre mine.

Since Kaulback & Veevers (1968) described the Cockatoo Formation of the Dillon Spring outlier, another section (425) has been measured; section 425 and its relations with the Matheson Ridge section are shown in Figure 15. The lower 1,150 feet consist of jointed white to yellow cross-bedded quartz sandstone indistinguishable from the type section of the Kellys Knob Member. A sequence of dominantly grey to green sandstone, sandy dolomite, and siltstone, identified as Kununurra Member, occupies the interval from 1,150 to 1,535 feet, and contains brachiopods, pelecypods, and conodonts at its base. The next unit, from 1,535 to 2,090 feet, identified as the Abney Member, is a dominantly red sandstone, part of it pebbly; pelecypods, discovered by Traves (1955, pp. 60-1), are found near the base. The uppermost unit, from 2,090 feet to the exposed top at 2,450 feet, is a jointed yellow to pink cross-bedded sandstone, readily identified as the Cecil Member.

No further comment on the poorly exposed probable Cockatoo Formation of the Mount Rob outlier (Kaulback & Veevers, 1968) is made, except that the glauconitic sandy dolomite with trace fossils near the exposed top is possibly part of the Kununurra Member.

Eastern Margin of Basin, from South of the Burt Range Amphitheatre to the Ochre Mine

A few miles south of the Burt Range Amphitheatre (Fig. 39), the Ragged Range Member unconformably overlies a quartz-feldspar porphyry, identified as the Precambrian Whitewater Volcanics (C. M. Morgan and I. Sweet, BMR, pers. comm.). Traves (1955, p. 73, figs 23 & 30) identified the underlying rocks as Precambrian metamorphics, and Matheson & Teichert (1948, p. 85) as Precambrian rhyolitic porphyry.

Nigli Gap Area

The only published account of the geology of the Nigli Gap area is by Traves (1955); he proposed the name Nigli Gap Sandstone for the sandstone that crops out in Nigli Gap, and included it in the Weaber Group, which he regarded as Permian. According to his description 'the sediments are essentially arenaceous, and most of the formation is of sandstone with numerous rafted pebbles. The unit also includes conglomerate members throughout the sequence, although the most significant conglomerate member occurs at the base' (p. 72). 'The poorly bedded, unsorted nature of these conglomerates suggests a glacial origin, although no evidence of glacial abrasion on faces of the boulders was observed' (p. 73). 'Specimens of *Equisetales* stems were examined in the rafted-pebble sandstone at locality 26 in Nigli Gap. . . . Associated with the rafted-pebble sandstone at the eastern end of Nigli Gap is an old volcanic vent of vesicular and scoriaceous trachyte which has apparently been injected along an old fault line. . . . The vent was probably of the explosive type, with little, if any, lava flow. Four miles south of this vent on the same fault line is an outcrop of vesicular trachyte, with billy at its contact with the rafted-pebble sandstone, and fine siliceous veins penetrating the sandstone' (p. 74).

From our study of the Nigli Gap area (Fig. 16; Pl. 7, fig. 1), we present another interpretation. We identify the sequence of mylonitized acid igneous rock, amygdaloidal volcanics, red-brown conglomerate and pebbly sandstone, and yellow sandstone as Halls Creek Metamorphics, Antrim Plateau Volcanics, Ragged Range Conglomerate Member, and Kellys Knob Sandstone Member. This sequence can be matched with similar sequences of these units in nearby areas.

Three contradictions remain unresolved. Firstly, according to A. A. Öpik (BMR, pers. comm.), who studied this area with Traves, the *Equisetales* stems are Upper Carboniferous or Permian, or even younger. We did not find these fossils, and hence cannot challenge this dating. Secondly, we did not see the critical outcrops where Traves and Öpik (Öpik, pers. comm.) found evidence of vulcanism contemporaneous with deposition of the sandstone. The volcanics exposed at the eastern end of Nigli Gap consist of severely altered amygdaloidal trachyte or alkaline basalt, which are commonly found as volcanic flows. The trachyte or basalt is underlain by closely jointed and mylonitized acid igneous rock, identical with that in outcrops of Precambrian Halls Creek Metamorphics 1 mile to the north-northeast (Fig. 16, loc. 74). There remains the possibility that the contemporaneous volcanics seen by Traves and Öpik are a separate younger unit. Thirdly, we failed to find evidence that the conglomerates are glacial—to us they are indistinguishable from outcrops of the Ragged Range Member that contain marine fossils.

The conflicting evidence indicates the need for a detailed re-examination of the Nigli Gap area.

Northwest of Nigli Gap, the Ragged Range Member can be identified on the air-photographs by its uniform soft dark grey tone, which contrasts with the light tone and fine pattern of close joints in the overlying Kellys Knob Member. Locality 417/1 (Fig. 39) contains 45 feet of exposed Ragged Range Member, including at the top 15 feet of conglomerate, notable for the presence of cobbles of basalt and Precambrian siltstone besides the common fragments of metaquartzite. Outcrops of the Ragged Range Member are not found between the Amphitheatre Fault and the Martin Bluff area.

The only other member of the Cockatoo Formation between Cockatoo Spring and Spirit Hill is the Kellys Knob Member, which crops out almost continuously. It contains variable amounts of pebbles and cobbles, it conformably overlies the

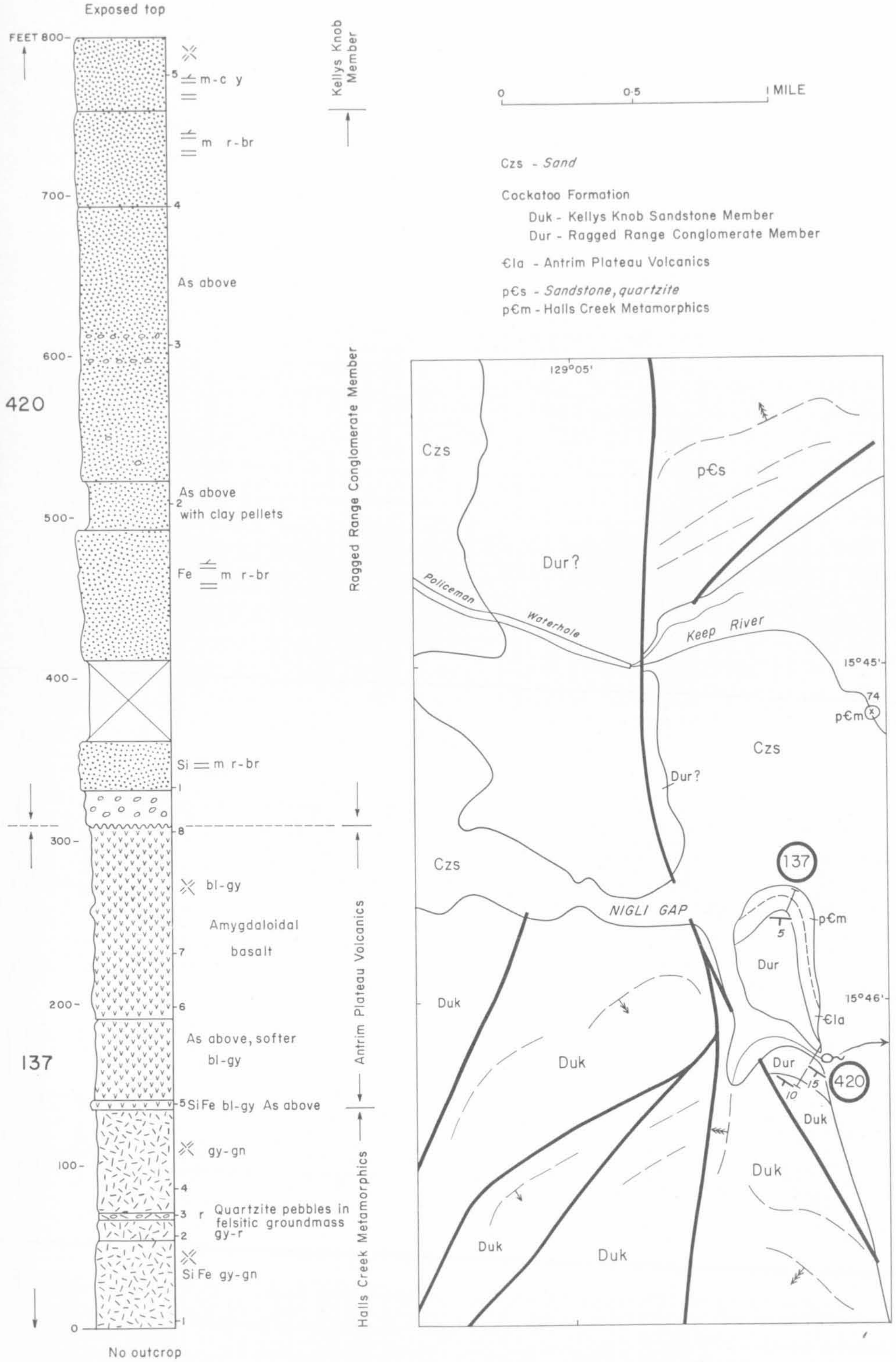


Figure 16. Geological map and columnar section, Nigli Gap area

Ragged Range Member, its top is eroded, and it is bounded on the east by faults. This outcrop of the Kellys Knob Member corresponds to Traves' Nigli Gap Sandstone.

One mile east of Spirit Hill (Fig. 53), sandstone, identified as the Kellys Knob Member of the Cockatoo Formation, crops out on either side of the Cockatoo Fault; to the east it rests on the Precambrian (Pl. 7, fig. 2). The Kellys Knob Member here is a cross-bedded medium to coarse-grained white quartz sandstone, which is conglomeratic at the base, and the Precambrian is a white quartzite.

Four miles northeast of Spirit Hill (Fig. 17), a butte 1 mile long consists of Precambrian siltstone overlain by Antrim Plateau Volcanics and the Ragged Range and Kellys Knob Members of the Cockatoo Formation. Traves (1955, p. 74) mapped a similar sequence at his localities 27 and 28 as Permian Weaber Group. Glover (App. A *in* Traves, 1955) has described the petrography of the volcanics from this butte and from Alpha Hill, 5 miles to the northeast (locs 24, 25, 26, 35, & 36 of Traves) and identified them as flows of amygdaloidal sanidine trachyte. We have mapped these lavas as Antrim Plateau Volcanics because they lie between the Precambrian and fossiliferous Upper Devonian along the eastern margin of the basin. All the volcanics along the eastern margin, however, are more alkaline than the typical basalts in the Antrim Plateau Volcanics. Traves' fossil localities 18, west of the butte, and 19, 2 miles to the southwest, are identified as Burt Range Formation.

In the northern part of the butte at locality 135/1 (Fig. 17), the Precambrian siltstone is unconformably overlain by red and buff sandstone and conglomerate of the Ragged Range Member. The red quartz sandstone is coarse to medium-grained and locally pebbly; it is cross-bedded and has current lineation on some of the bedding planes. The conglomerate disconformably overlies the sandstone; it contains rounded boulders of quartzite up to 2 feet in diameter and small angular fragments of Precambrian siltstone, set in a matrix of feldspathic quartz sandstone. Overlying the conglomerate is a medium-grained buff quartz sandstone containing occasional trace fossils. The Ragged Range Member is in turn overlain by cliff-forming cross-bedded buff feldspathic quartz sandstone of the Kellys Knob Member. In the fault block west of this section, the Antrim Plateau Volcanics lie between the Precambrian siltstone and the Ragged Range Member. The Antrim Plateau Volcanics consist of copper-stained tuff and trachyte and overlie, with angular discordance, thin-bedded purple Precambrian siltstone. The trachyte and siltstone were faulted before the deposition of the overlying red sandstone and conglomerate of the Ragged Range Member.

The Antrim Plateau Volcanics are missing in the westernmost and easternmost fault blocks, probably because the blocks were uplifted and the cover of volcanics removed by erosion before the Ragged Range Member was deposited.

Similar sequences were found 5 miles northwest in the Alpha Hill area (Fig. 18). At Alpha Hill itself (Fig. 18, section 134; Pl. 8, fig. 1) the Precambrian and Antrim Plateau Volcanics are unconformably overlain by 50 feet of red conglomerate, which in turn is overlain by 235 feet of grey, buff, yellow, and red sandstone which we identify as interfingering Ragged Range Member and Kellys Knob Member. The Antrim Plateau Volcanics contain interbeds of silicified sandstone, boulders of which constitute a large part of the overlying conglomerate.

The boulders are angular to subrounded and average up to 3 feet across; they are set in a matrix of basalt fragments and coarse sandstone stained by red ochre. The conglomerate is overlain, apparently conformably, by cliff-forming sandstone.

Half a mile to the north at locality 121, the Antrim Plateau Volcanics are overlain by a thick sequence of white quartz sandstone and conglomerate identified as Kellys Knob Member; either the Ragged Range Member was stripped off, because the block north of Alpha Hill was faulted up before the Kellys Knob Member was deposited, or the Ragged Range Member accumulated in depressions, and the overlying Kellys Knob Member locally overlapped it. The Kellys Knob Member consists of medium to coarse-grained quartz sandstone containing lenses of conglomerate, and is silicified at the base. Poorly preserved pelecypods were collected at locality 121/2.

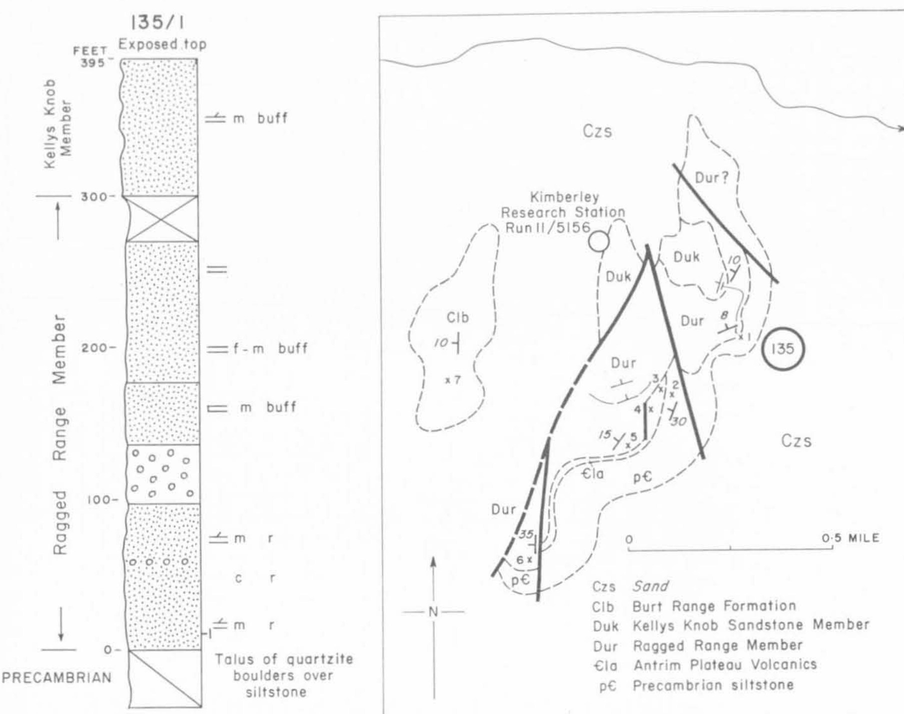


Figure 17. Geological map and columnar section of butte 4 miles southwest of Alpha Hill

A sequence similar to that at Alpha Hill crops out at the Ochre mine (Fig. 45), 8 miles west of Alligator Springs. Poorly exposed white Precambrian siltstone is overlain by hematitized and silicified Antrim Plateau Volcanics which, in turn, are overlain by the Ragged Range Member. The basal conglomerate of the Ragged Range Member is 20 feet thick; it contains slabs of siltstone, boulders of quartzite, interbeds of shaly siltstone containing clay pellets, and pebbly quartz sandstone. The conglomerate is overlain by a fine siltstone composed mainly of red ochre, followed by a fine to medium-grained red quartz sandstone containing *Leptophloeum australe* (M'Coy). The ochre mine has been described by Traves (1955, pp. 105-6).

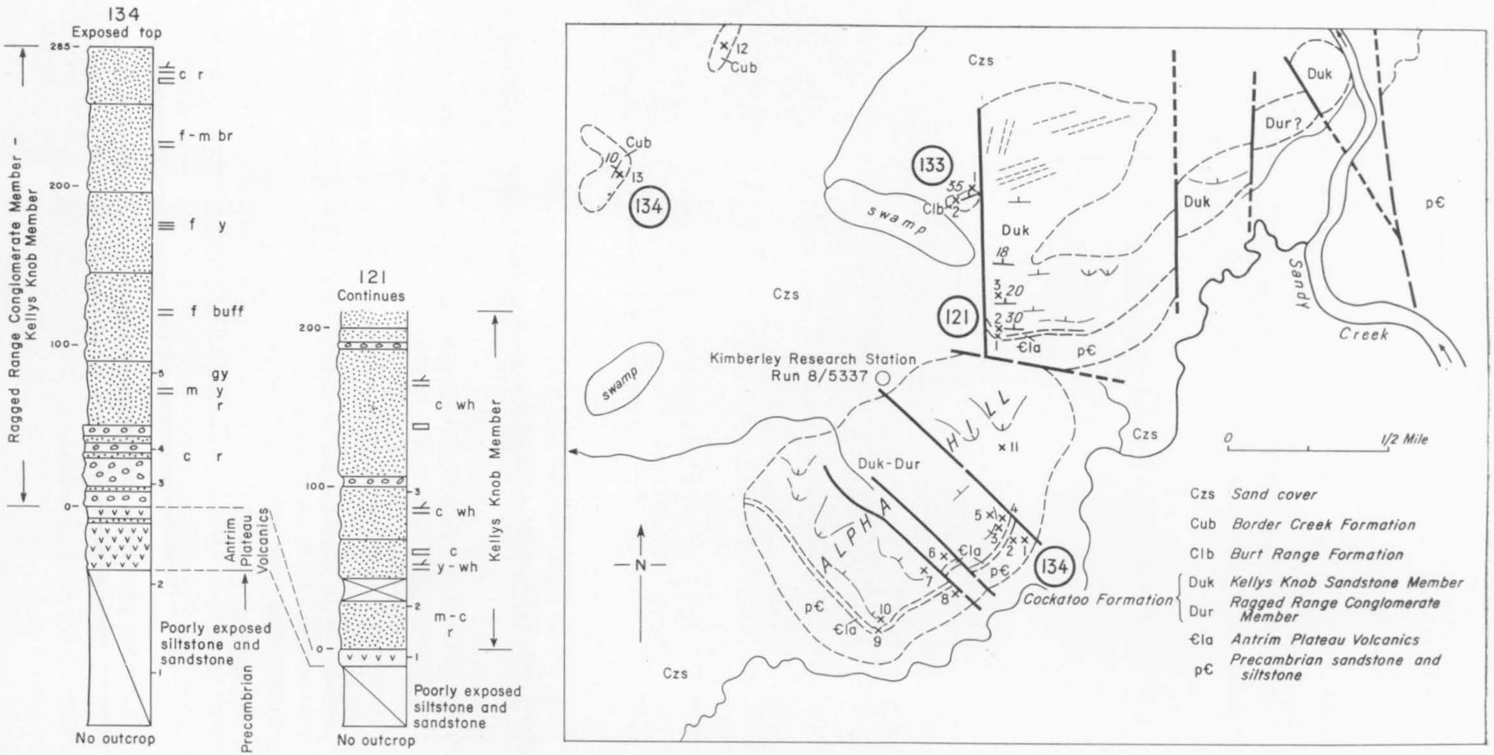


Figure 18. Geological map and columnar sections, Alpha Hill area

Sandstone identified as Kellys Knob Member crops out alongside the Carlton Hill/Legune track near Sandy Creek, and appears to rest directly on Precambrian siltstone.

Cross-bedded white quartz sandstone, identified as Kellys Knob Member, which also apparently overlies the Precambrian basement, crops out in hills 5 miles west of Alligator Springs. The absence of the Ragged Range Member at both these localities is due to the erosion of the upfaulted blocks before the deposition of the Kellys Knob Member, or to overlap of the Kellys Knob Member on the Ragged Range Member that filled the underlying depressions.

The northernmost outcrops of the Cockatoo Formation are two isolated turrets of fawn to white quartz sandstone, identified as Kellys Knob Member, at locality 124/2 near Legune station (Fig. 45).

Two hillocks 2 miles south of Sorby Hills (for reasons of space, shown as a single outcrop on Map 1) contain the only known outcrops of the Antrim Plateau Volcanics and Cockatoo Formation along the eastern edge of the Pincombe Range. The larger hillock is conical, and consists of 10 feet of basalt, identified as Antrim Plateau Volcanics, overlain by about 140 feet of blocky silicified micaceous quartz sandstone, feldspathic quartz sandstone, and laminated quartz sandstone with clay galls, which are identified as Cockatoo Formation, and tentatively as the Kellys Knob Member. Most of the sandstone exposed consists of loose blocks, but the few blocks in situ indicate that the bedding is horizontal. (The conical form of horizontal silicified sandstone of the Cockatoo Formation is also found at Church Steeple Peak, which consists of fault-bounded Antrim Plateau Volcanics overlain by loose blocks of silicified sandstone of the Ragged Range Member, and at Cone Hill, where the sandstone blocks probably represent Cecil Member over Westwood Member.) These two small outcrops on the eastern edge of the Pincombe Range clearly show that the Antrim Plateau Volcanics and Cockatoo Formation extend from the eastern edge of the basin across to the Pincombe Range, and that the general structure of this part of the basin is a graben, or syncline, or both. The Buttons Beds, which rest unconformably on the Precambrian siltstone in the Sorby Hills, are the only locally transgressive deposits which extend a short distance beyond the edge of the graben or syncline.

This concludes the description of the Cockatoo Formation in the platform conglomerate province. Another outcrop, which lies on the western flank of the Pincombe Inlier, in the platform carbonate province, is also described here because it contains pebbles and cobbles indicative of the marginal province. It is an isolated outcrop of sandstone at Buttons Crossing (Fig. 35), on the Ord River, which has been described by Matheson & Teichert (1948, p. 84). About 1,000 feet of jointed cross-bedded quartz sandstone, with minor beds of pebbly and cobbly sandstone, dips at 20° to the northeast. Some of the beds have a weak calcareous cement. Poorly preserved pelecypods were found near the exposed base. In view of the complex and largely obscured structure of the area, extrapolations from the Buttons Crossing outcrop are speculative. The outcrops of Antrim Plateau Volcanics a little over half a mile upstream are probably separated from the sandstone by the covered inferred fault shown in Figure 35. In the other direction, the outcrops of Buttons Beds half a mile downstream are apparently concordant structurally with the sandstone, as suggested by Matheson & Teichert (1948, p. 84). However, the faults with large displacements in this area leave little or no visible trace, as exemplified by the inferred fault with an estimated throw of 6,000 feet separating the Buttons Beds and Cambrian Clark Sandstone (Fig. 35). If the Buttons Beds and Cockatoo Sandstone are conformable in this area, as they are elsewhere in the basin, the outcropping sandstone would represent the Cecil Member, and the covered interval between the outcrops would probably be underlain by the Jeremiah Member. This interpretation is supported by J. M. Dickins' (BMR, pers. comm.) recognition of the pelecypods as different from those in the middle part of the formation.

Platform Carbonate Province

Southern Part

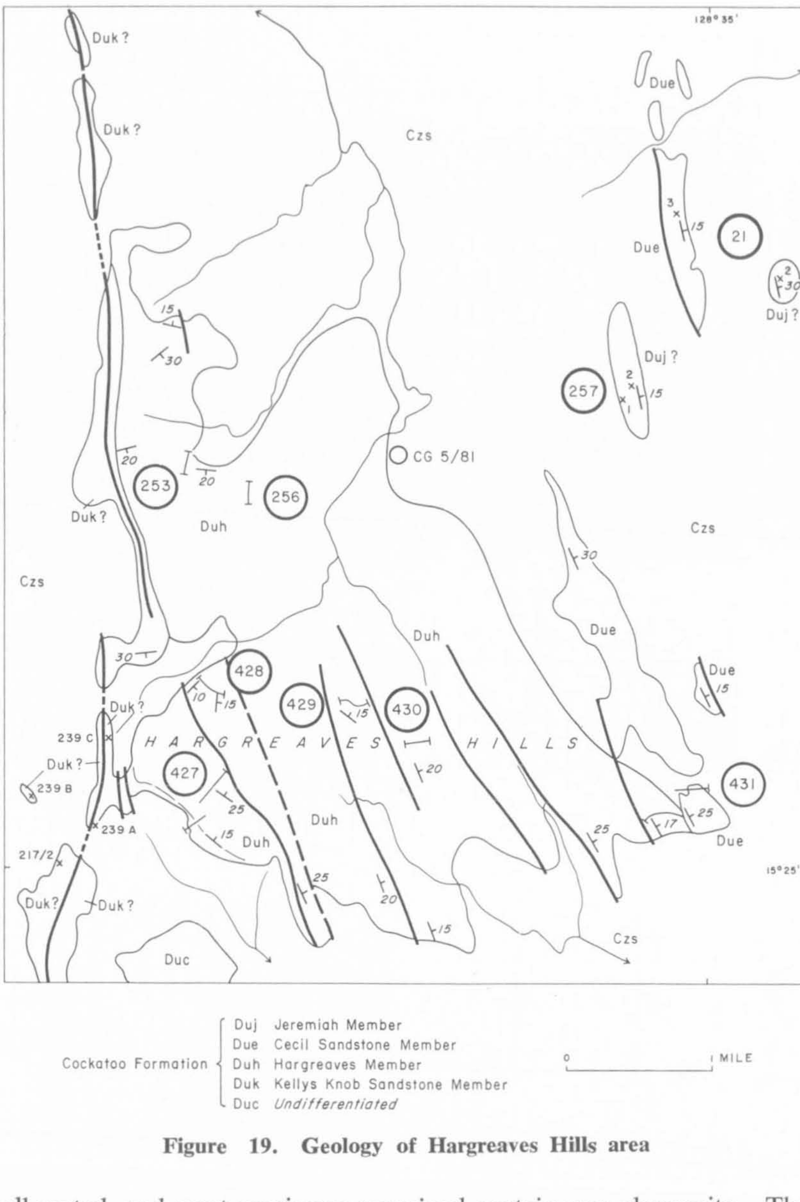
The area between the Pincombe Range and the northern part of the Hargreaves Hills contains inclined strata crossed by numerous prominent strike faults of large throw, which tend to mask less prominent faults. Furthermore, because the sequence is monotonous, clear connexions between fault blocks cannot be found. In the Hargreave Hills we have therefore measured sections which appear to contain the least disturbed sequences, and in choosing the sections, we were guided by the detailed work in this area by the Australian Aquitaine Petroleum geological party.

The quartz sandstone exposed on either side of the fault that marks the western edge of the Hargreaves Hills (Fig. 19) has been tentatively identified as Kellys Knob Member on the basis of its general lithology, as its stratigraphical position, because of faults, is not known. The only distinctive feature of this sandstone, if indeed it belongs to this member, is its thick cross-bedding, seen at localities 239A-C and 217/2. The sets of cross-strata are more than 20 feet thick, which suggests that the beds are aeolian, although this thickness also lies within the size range of aqueous cross-beds.

Hargreaves Member (new name)

The Hargreaves Member is here defined as the tabular body of varicoloured fine-grained quartz sandstone, dolomitic quartz sandstone, sandy dolomite, and marl that conformably underlies the Cecil Member in the Hargreaves Hills (Fig. 19). The interval from 0 to 720 feet of section 431 (Fig. 20) is designated as the type section; sections 427, 428, 429, and 430 are supplementary. The co-ordinates of the base of the type section are latitude 15°20′S., longitude 128°35′E. The base of the type section is marked by a fault, and the top is conformably overlain by the Cecil Member. The type section comprises 720 feet of laminated to medium-bedded fine-grained yellow, green, and white quartz sandstone, with minor beds of dolomite and dolomitic sandstone. Pelecypods, brachiopods, conodonts, fish plates, and trace fossils were found at two localities. Part of section 431 was chosen as the type section because it is the only one of our measured sections in the Hargreaves Hills where the stratigraphical relations with another member are clear. The relations of section 431 with the other measured sections in the Hargreaves Hills, as shown in Figure 20, are conjectural, as there is no suitable marker to provide a link between the fault blocks. The correlations between sections 427, 428, and 429 are based on the recognition of markers or sequences of markers in different fault blocks: we are aware of the shortcomings of this method, and the scheme shown in Figure 20 is tentative only.

With these reservations, the Hargreaves Member is thought to consist of more than 2,000 feet of generally thin to medium-bedded fine-grained quartz sandstone, with minor dolomitic sandstone, sandy dolomite, and marl. The quartz sandstone is readily distinguished from that of the Cecil Member because it is fine-grained



Cockatoo Formation
- Duj Jeremiah Member
- Due Cecil Sandstone Member
- Duh Hargreaves Member
- Duk Kellys Knob Sandstone Member
- Duc *Undifferentiated*

0 — 1 MILE

Figure 19. Geology of Hargreaves Hills area

and well sorted, and most specimens examined contain rare glauconite. The sandstone is friable, and is weakly cemented by quartz overgrowths. Most of the sandy dolomite and dolomitic sandstone consists of varying amounts of well sorted fine quartz sand in a matrix of mosaic dolomite.

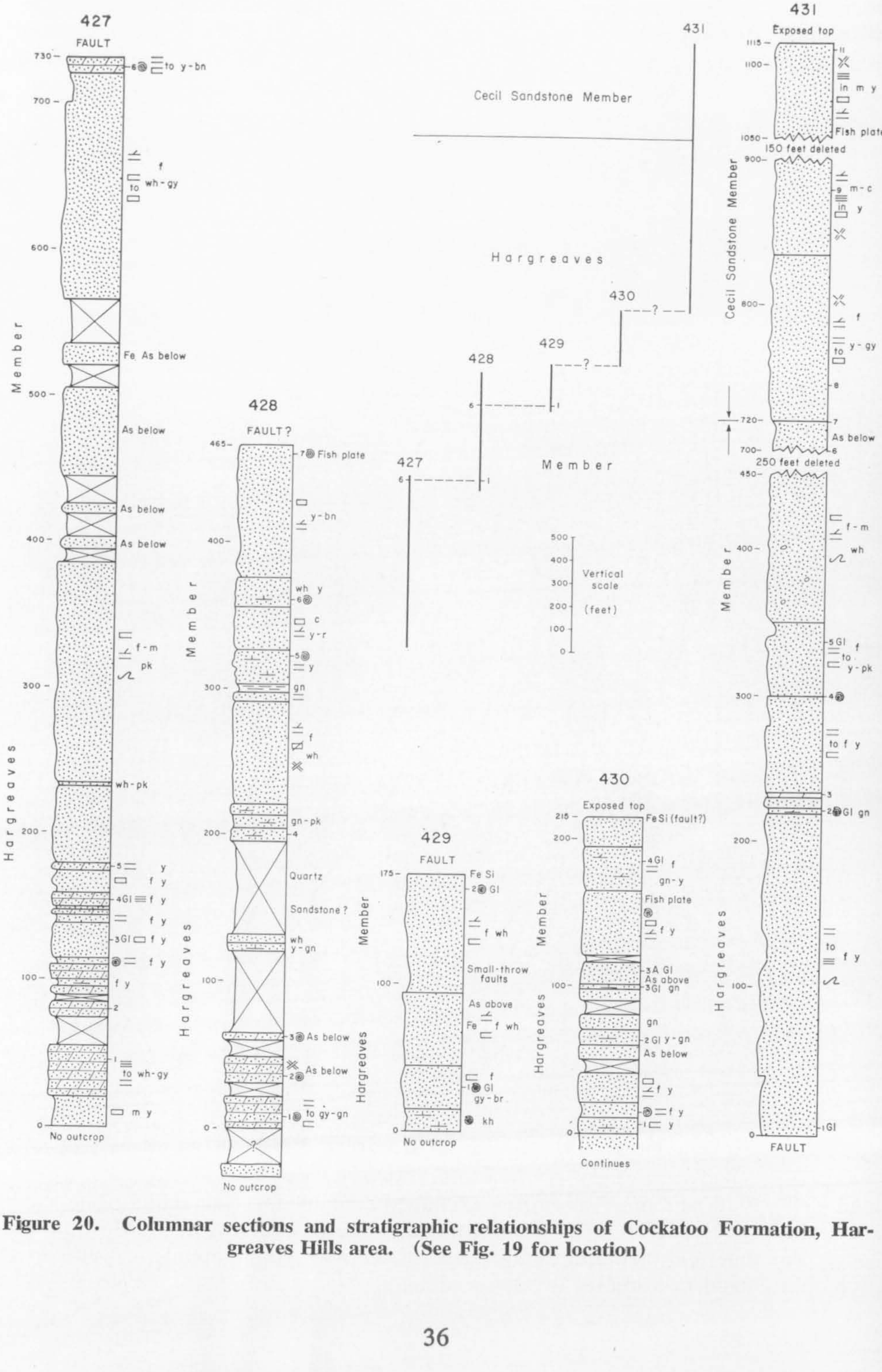


Figure 20. Columnar sections and stratigraphic relationships of Cockatoo Formation, Hargreaves Hills area. (See Fig. 19 for location)

The outcrops of the Hargreaves Member are etched into numerous sharp strike ridges and valleys which contrast with the bluffs of Kellys Knob Member(?) at the western edge of the Hargreaves Hills and of the Cecil Member at the eastern edge.

Poorly preserved pelecypods, brachiopods, trace fossils, and fish plates were found at 12 different horizons.

A composite section (Fig. 19, sections 253 & 256) through part of the Hargreaves Member was measured 1½ miles north of locality 428. The measured thickness of 400 feet consists of roughly equal proportions of interbedded quartz sandstone and sandy dolomite, and includes a single bed with pelecypods. What part of the Hargreaves Member is represented by the section is not known.

The Hargreaves Member was recognized in various parts of the Pretlove Hills, but, owing to the intense strike faulting, the area was not mapped in detail. A small fault block of dolomite and fossiliferous marl 2 miles east of Clark Jumpup has been described by Traves (1955, p. 61, fig. 22). In another paper, Veevers & Roberts (1966) argue that the Hargreaves Member in the Pretlove Hills was the chief source of the blocks of dolomite in the Visean Waggon Creek Breccia.

Other Members

The jointed cross-bedded sandstone marking the western edge of the Hargreaves Hills has been tentatively identified as Kellys Knob Member; it can be traced to the south and southeast along a major fault into the Pretlove Hills, where it is juxtaposed against outcropping Cambrian sediments (Figs 21, 22, & 23).

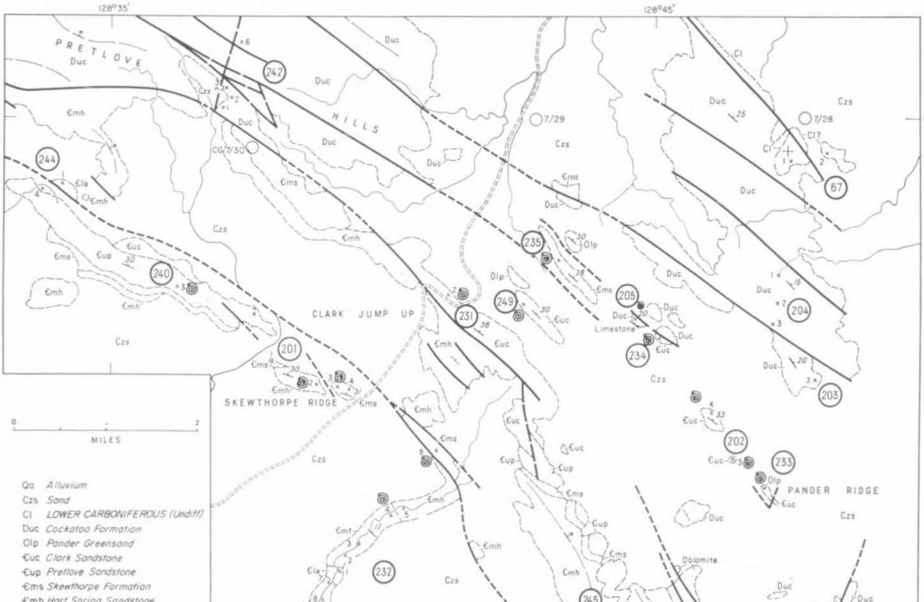


Figure 21. Geology of southern and central Pretlove Hills. (After Kaulback & Veevers, 1968)

About 500 feet of friable quartz sandstone are exposed in the cliff face of a large fault block in the Onslow Hills, 2½ miles east of Hart Spring (Fig. 23, loc. 222). The sandstone is cross-bedded in thick sets, and is probably part of the Kellys Knob Member.

Another outcrop of Kellys Knob Member(?) occurs between Point Spring and Jeremiah Hills (Fig. 24). At locality 423/5, barren fine-grained silicified yellow quartz sandstone, probably the Kellys Knob Member, unconformably overlies fossiliferous red and white quartz sandstone, some of it glauconitic, which has been identified as Cambrian Clark Sandstone. Localities 423/4, 6, and 7 all contain trilobites. This is the only locality known to us where an unfaulted contact between the Cockatoo Formation and Cambrian sedimentary rocks is visible. The closely faulted sandstone at locality 423/8 is also probably Kellys Knob Member. The other outcrops in this area are Ningbing Limestone.

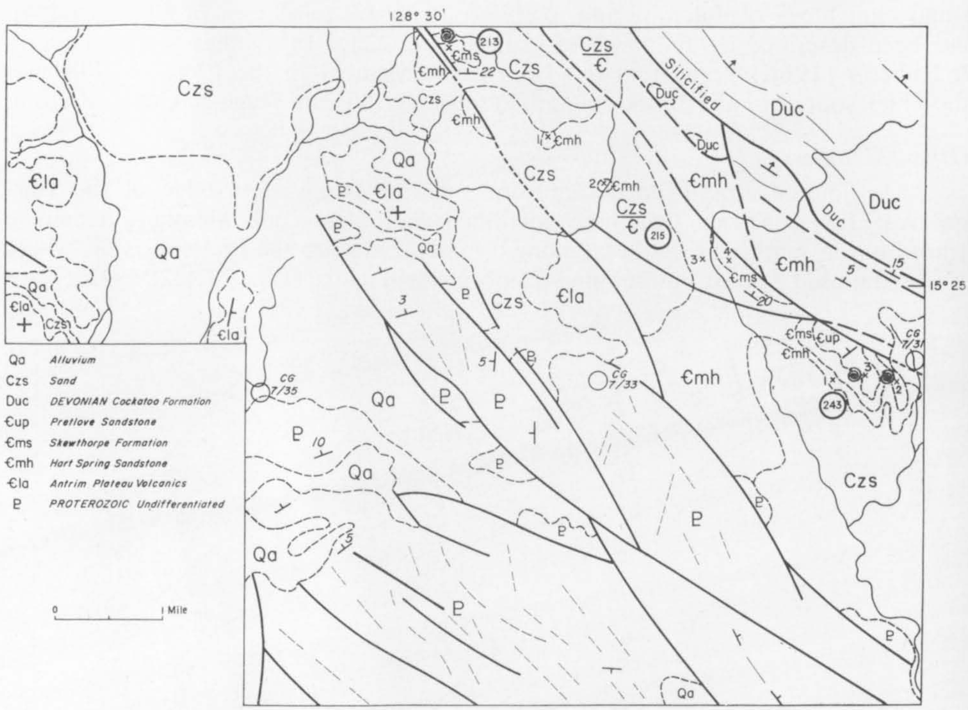


Figure 22. Geology of northern Pretlove Hills. (After Kaulback & Veevers, 1968)

The Cecil Member probably occupies a large part of the northern Pretlove Hills, as shown, for example, by the outcrop of dipping sandstone (Cecil Member?) at the Carlton-Legune road crossing of Redbank Creek (Pl. 8, fig. 2).

The Cecil Member on the eastern edge of the Hargreaves Hills conformably overlies the Hargreaves Member, and about 400 feet of it is exposed in the area (Fig. 20, section 431). As elsewhere, so here the Cecil Member is deeply jointed and strongly cross-bedded. The only fossil found in the section was a fish plate.

Because of the lack of outcrops and dislocation by faults to the east of Hargreaves Hills the total thickness of the Cecil Member in this area has not been

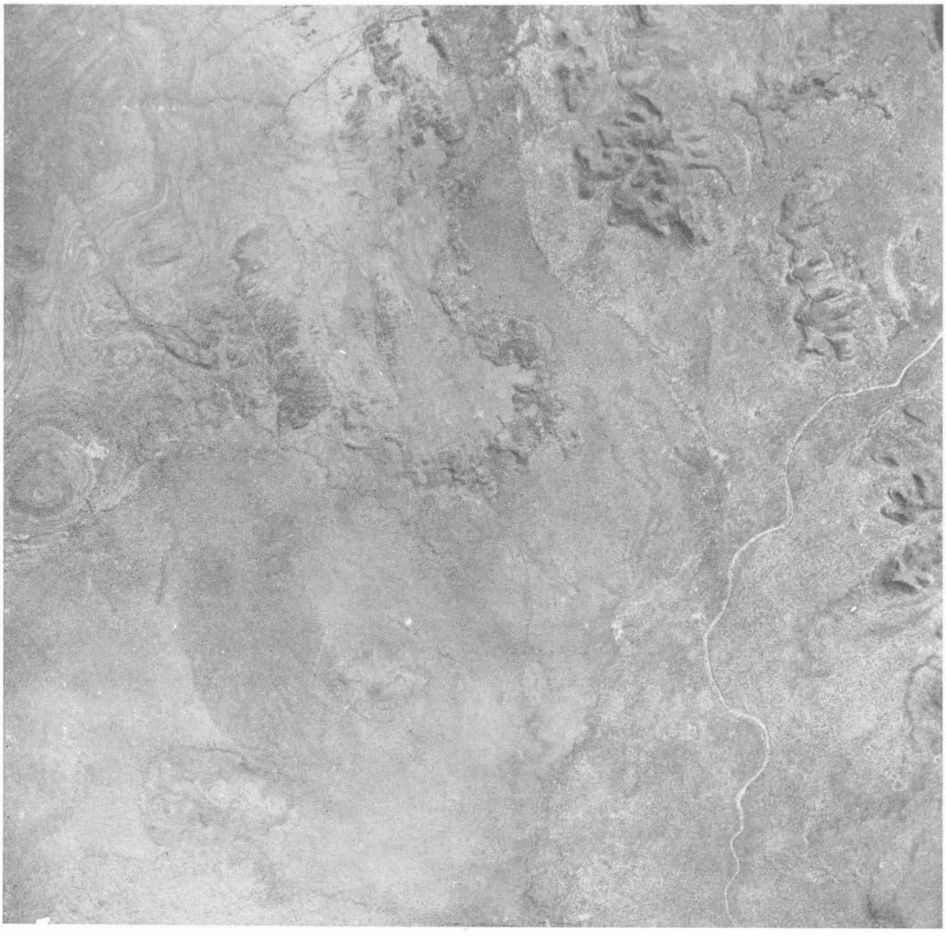


Plate 15. Vertical air-photograph (Cambridge Gulf, Run 5/5178) of southern part of Ningbing Range and southwestern part of Weaber Range. For explanation see Figure 31

Plate 16, Figure 1. Looking west at back-reef limestone of Ningbing Limestone at southernmost tip of Ningbing Range. Photo: J. Zawartko

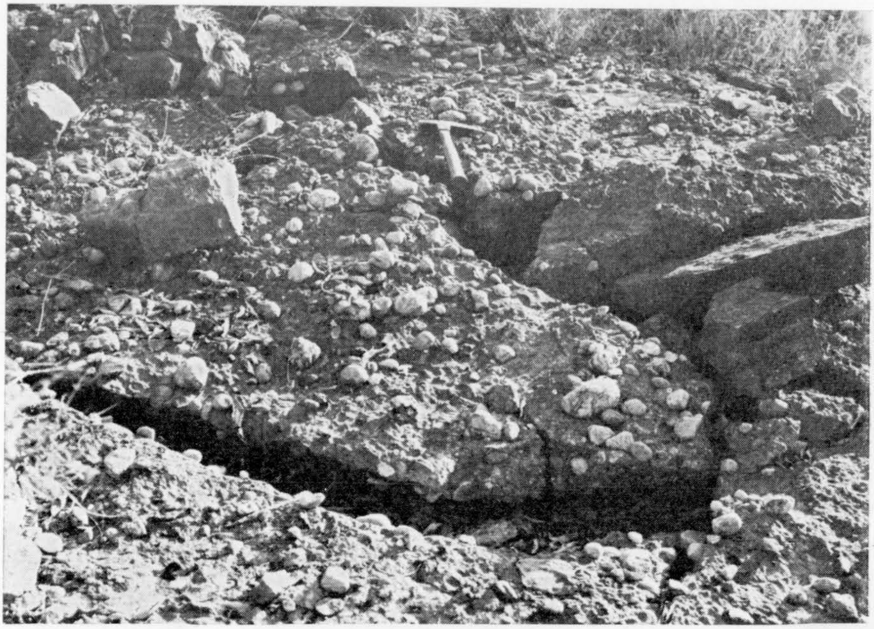


Plate 16, Figure 2. Pebbles and cobbles of quartzite and dolomite on surface of limestone conglomerate in the back-reef of the Ningbing Limestone at locality 21-25, near Siggins Spring

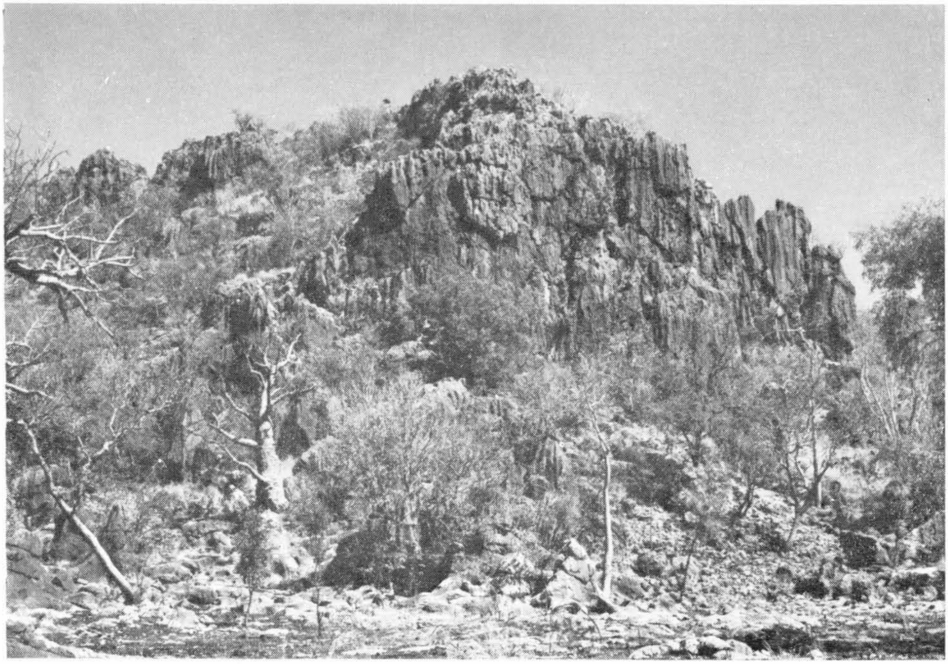


Plate 17. Close-up of Figure 32 showing fluted massive reef limestone. Photo: C. Zawartko

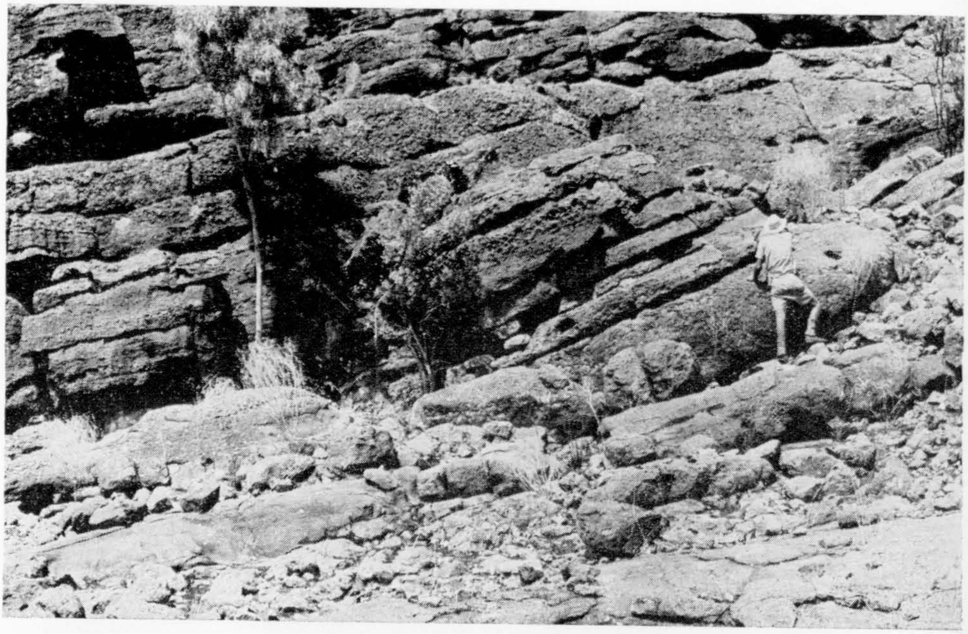


Plate 18, Figure 1. Fore-reef breccia of the Ningbing Limestone at locality 17-4, 1 mile north of Surprise Creek

Plate 18, Figure 2. Close-up of preceding figure, showing angular to rounded fragments of limestone in well-layered fore-reef breccia of the Ningbing Limestone

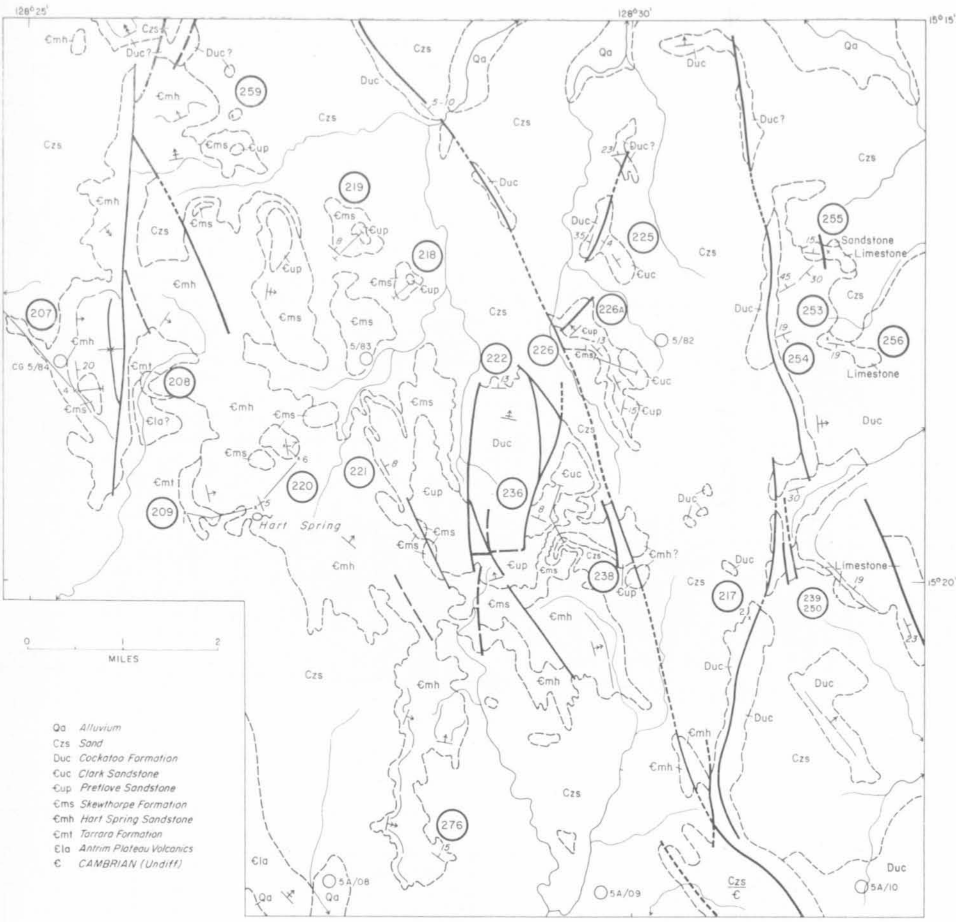
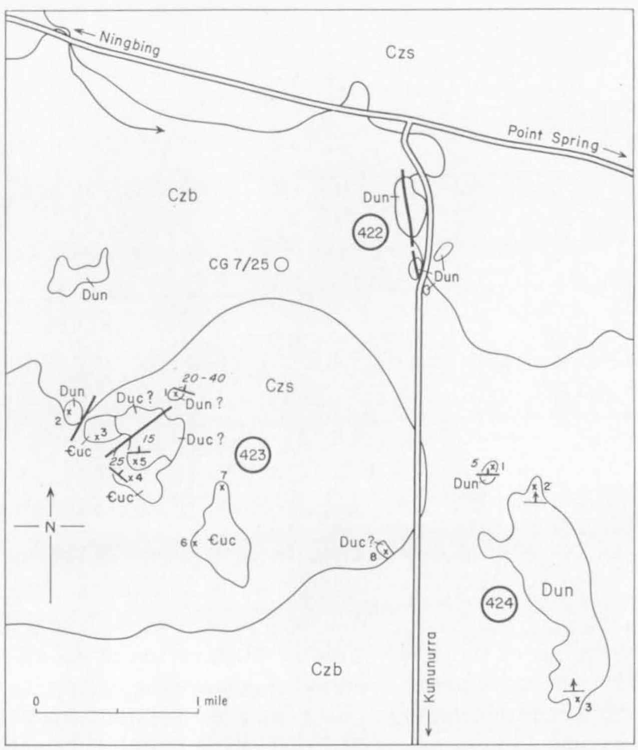


Figure 23. Geology of Onslow Hills. (After Kaulback & Veevers, 1968)

estimated. To the east, the first outcrops of a known younger unit are those found west of Siggins Spring in the headwaters of Mistake Creek (Fig. 31, section 21; Fig. 25). The scattered outcrops consist of glauconitic quartz sandstone, sandy limestone, and dolomite (including oolite), and are overlain, apparently conformably, by the Ningbing Limestone. Pelecypods were found at locality 21/12. The estimated stratigraphical thickness of 1,240 feet between the oldest exposure in the core of the anticline and the base of the Ningbing Limestone may include beds repeated by concealed faults. The beds are identified as part of the Jeremiah Member. The carbonate rocks and sandstone at localities 257 and 21/2 (Fig. 19) are tentatively identified as the Jeremiah Member.

Jeremiah Member (new name)

The Jeremiah Member is here defined as the sequence of sandy limestone and dolomite, with minor interbedded sandstone, that conformably underlies the Ningbing Limestone in the Jeremiah Hills (Fig. 26). The interval from 0 to 360 feet in section 442 (Fig. 25) is designated as the type section. The co-ordinates of the base of the type section are latitude 15°12′S., longitude 128°44½′E. The base of the type section is marked by a fault, and the top is conformably overlain by the Ningbing Limestone. The type section comprises brown, red, and yellow-grey sandy dolomitic limestone, which is thinly to very thickly bedded, with minor interbeds of dolomitic quartz sandstone. Brachiopods, conodonts, and crinoid ossicles were found at four localities. The regular bedding and subdued morphology of the Jeremiah Member serve to distinguish it on the air-photographs from the crags of the overlying Ningbing Limestone. Outcrops of the Jeremiah Member were found beneath the Ningbing Limestone in the southern half of the Jeremiah Hills, and a measured section (444) from the eastern edge of the Jeremiah Hills is also shown in Figure 25. Section 444 contains more sand at its base than the equivalent part of section 442.



Czb *Black soil*	Dun *Ningbing Limestone*	€uc *Clark Sandstone*
Czs *Sand*	Duc *Cockatoo Formation*	

Figure 24. Geology of area 5 miles west-southwest of Point Spring

The interval 0 to 1,240 feet in section 21 (Fig. 25) has been mentioned already. The only other known outcrops of the Jeremiah Member are in the platform conglomeratic province.

Isolated outcrops (Fig. 11, loc. 60) are found in the bed of Eight Mile Creek, 1½ miles east of Mount Cecil; they consist of varicoloured sandy dolomite, dolomitic sandstone, and marl. The section is too poorly exposed to be measured. The geologists of Australian Aquitaine Petroleum (pers. comm.) found plant fossils (*Leptophloeum?*) at this locality.

The very low outcrops (Fig. 39, loc. 100/2, 3) on the plain 1 mile north of section 146 consist of medium-grained yellow to white quartz sandstone with *Leptophloeum* and indeterminate pelecypods. The faint strike lines visible on the air-photographs indicate that the sandstone at locality 100/2, 3 lies not far below the base of section 146, and it may belong to the upper part of the Cecil Member.

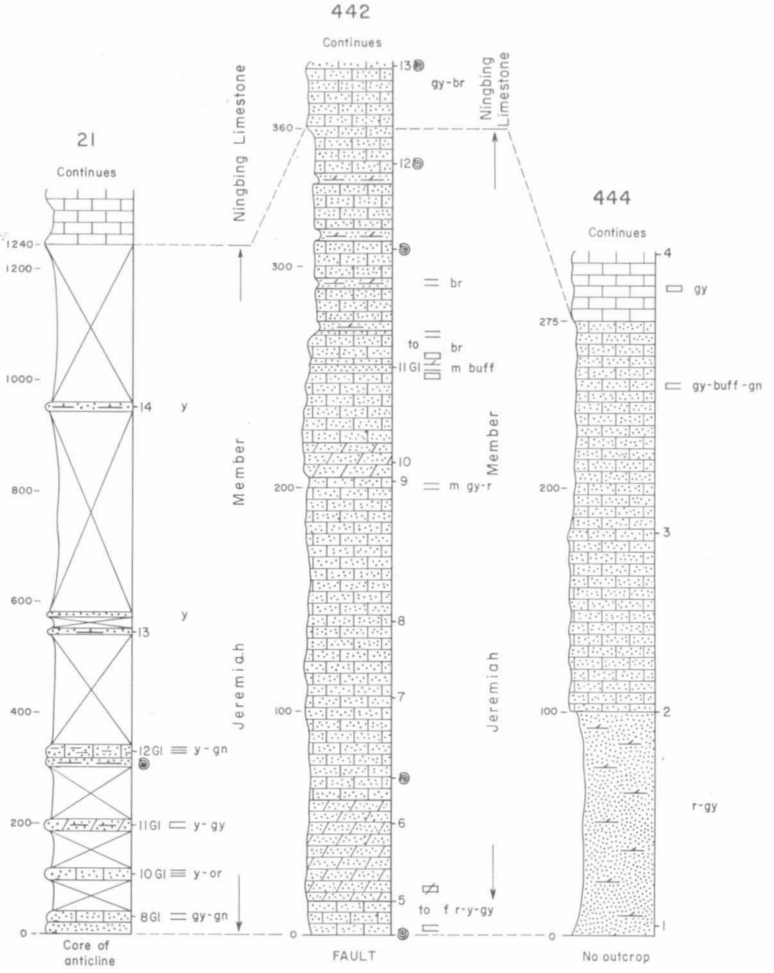


Figure 25. Columnar sections of Jeremiah Member, Cockatoo Formation. (See Figs 26 and 31 for location)

Exposures of the lower boundary of the Jeremiah Member have not been found, but in both the Siggins Spring and Eight Mile Creek areas the Jeremiah Member lies to the east of outcropping Cecil Member in an east-dipping sequence, and there is little doubt that the Jeremiah Member overlies the Cecil Member.

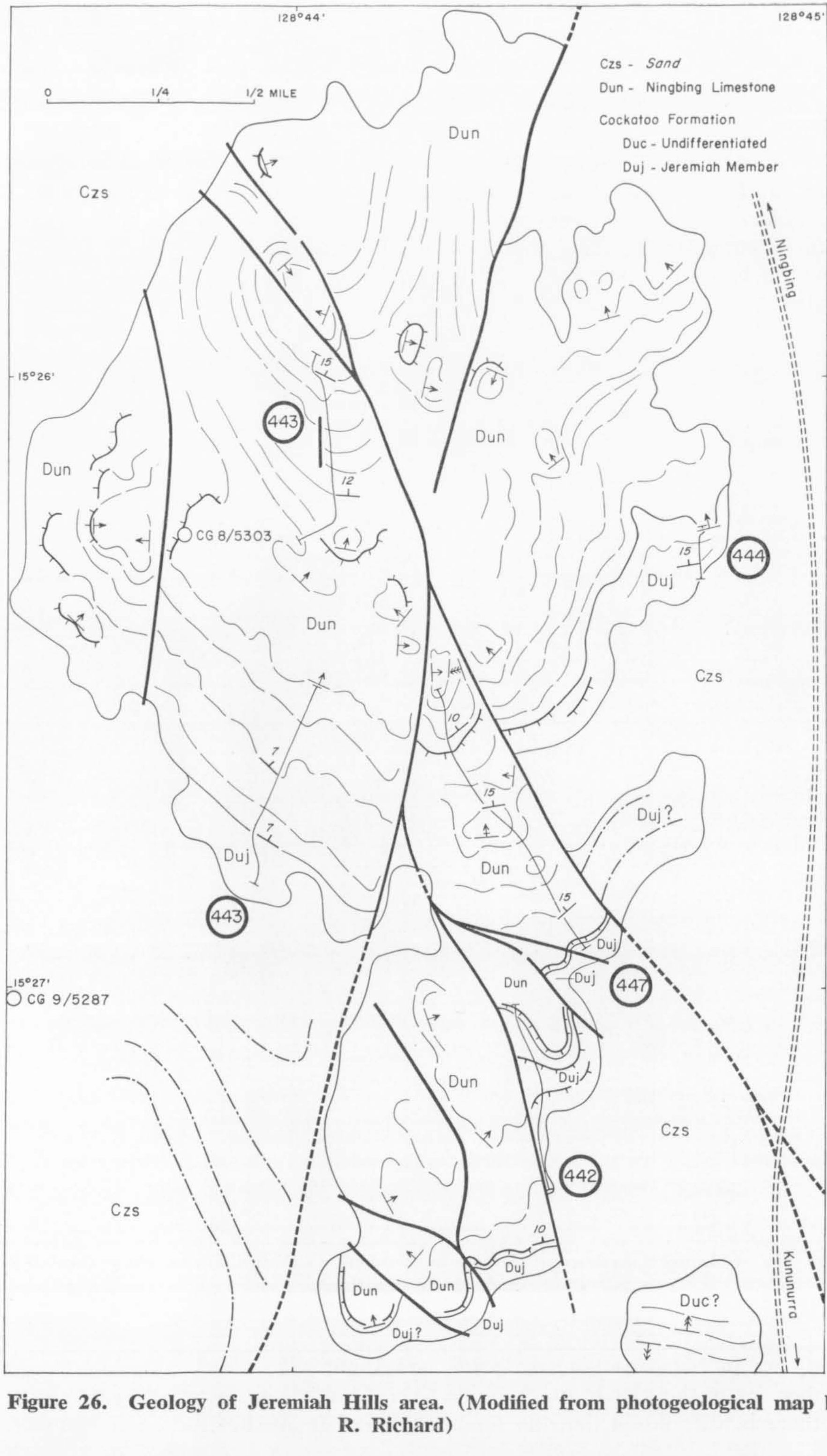


Figure 26. Geology of Jeremiah Hills area. (Modified from photogeological map by R. Richard)

Northern Part

The only extensive and structurally simple outcrops of the Cockatoo Formation north of Hargreaves Hills are those in the Westwood Creek area. All the other outcrops of Cockatoo Formation are isolated, and are complicated by faults to which their existence as outcrops is due. Thus, with the exception of the outcrops of Westwood Creek, none can be positively identified in terms of the members of the Cockatoo Formation. The only fossils found in the Cockatoo Formation in the area between Hargreaves Hills and Westwood Creek are the pelecypods and fish plates at Traves' (1955, p. 60) locality 3 (our locality 46/2), 3 miles west of Surprise Creek gorge. The fossiliferous thin-bedded sandstone is probably the Hargreaves Member, and the overlying jointed and cross-bedded coarse sandstone is probably the Cecil Member. Similar jointed and cross-bedded sandstone at locality 47 a few miles south of locality 46/2 is tentatively identified as Cecil Member.

Outcrops at localities 42-45, between Leichhardt Spring and the Onslow Hills (Map 1), are all tentatively identified as Kellys Knob Member. They consist of jointed cross-bedded ripple-marked medium to coarse quartz sandstones. At locality 43/7, the tabular cross-beds with an exposed thickness of 20 feet recall those at locality 239B, west of Hargreaves Hills, and are also aeolian or very large-scale subaqueous cross-beds. Farther north along this line of faults, and along those in the Gladys Spring/Leichhardt Spring area, similar sandstone is thrown down to the west against fossiliferous Cambrian Clark Sandstone (loc. 263).

Bald Hill (Map 1) consists of at least 1,000 feet of silicified quartz sandstone dipping to the north at 50° to 65°. It is faulted against an exposed 50 feet of subhorizontal barren sandy dolomite and barren coarse laminated pebbly quartz sandstone, which is either part of the Cambrian succession or, more probably, part of the Westwood Member of the Cockatoo Formation.

Elephant Hill (Map 1) is bounded on two sides by faults, and consists of silicified cross-bedded ripple-marked quartz sandstone. The large unnamed hill (loc. 40) 2 miles northwest of Elephant Hill consists of unsilicified quartz sandstone, regularly cross-bedded in tabular sets 2 feet thick. Ripple marks are common.

Virtually all our knowledge of the sequence of the Cockatoo Formation in the northwestern part of the basin comes from studies made in the Westwood Creek area (Fig. 27). The first published reference to the geology of this area was made by Veevers et al. (1964), who followed on E. P. Utting's (pers. comm.) discovery 5 years earlier.

Westwood Member (new name)

The Westwood Member is here defined as the thick sequence of interbedded limestone or dolomite and fine to medium thin-bedded quartz sandstone in the Westwood Creek area. Section 459 (Figs 27, 28; Pl. 9, fig. 1) is designated as the type section, and sections 12 and 13 complement it. The co-ordinates of the base of the type section are latitude 14°52′S., longitude 128°30′E. South of locality 460, the Westwood Member overlies, probably conformably, poorly exposed barren sandstone, which has been tentatively identified as Kellys Knob Member. The top of the Westwood Member is eroded in section 13, and elsewhere the upper part of the member is covered. There are 1,880 feet of dipping strata exposed almost continuously on the tidal flats in section 13 (Pl. 9, fig. 2). This section lies on the western limb of the pitching anticline shown in Figure 27, and sections 12 and 459 and, if the anticline continues so far south, section 460, are on the eastern limb.

The type section is 555 feet thick, and consists of sandy stromatolitic limestone (fore-reef(?) limestone) (Pl. 10, figs 1 & 2) interbedded with pelecypod coquinite and oncolite at the base (Pl. 11, figs 1 & 2) and overlain by interbedded sandy limestone (with solitary corals, stromatoporoids, brachiopods, pelecypods, gastropods, conodonts, and ostracods) and sandstone, with 100 feet of

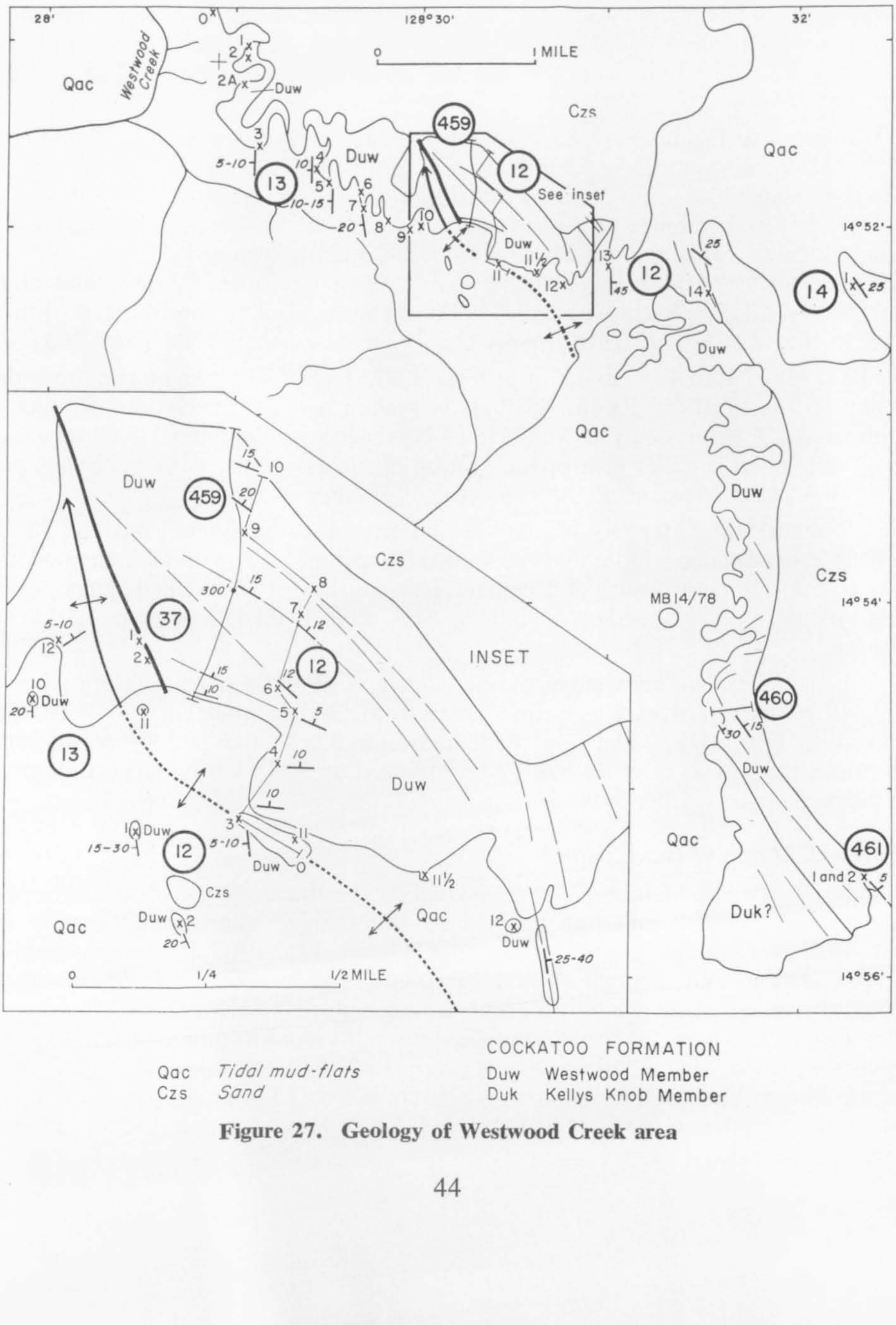


Figure 27. Geology of Westwood Creek area

jointed thin-bedded yellow-brown quartz sandstone at the top. The sandstone contains fish plates and the plant stem *Leptophloeum australe*. The lateral lithological changes between sections 459 and 12 include small differences in the quartz sand content of equivalent beds. Section 13, whose relations with the other measured sections are shown in Figure 28, is much sandier than its equivalents in the other sections, but poor exposure in the interval 100 to 430 feet rules out further comparison. Large colonies of corals (*Hexagonaria*) at locality 12/2 (Pl. 12, figs 1 & 2) on the western limb of the anticline, were not seen elsewhere in section 12. The upper part of the Westwood Member is seen in section 13 only, and consists of thin-bedded to laminated fine to medium yellow quartz sandstone with three thin interbeds of limestone. Beds with converging strike at locality 12/5 indicate rapid wedging or faulting.

Fossils have not been shown in the sections of Figure 28, because they are almost ubiquitous. Fossils in the limestone include algae, brachiopods, conodonts, corals, crinoid ossicles, gastropods, ostracods, pelecypods, and stromatoporoids (Pl. 13); and in the sandstone, brachiopods, ostracods, pelecypods, and plants. The build-up of stromatolites and the abundance of *Renalcis,* a reef alga, in the conical outcrops of limestone breccia in the basal 100 feet of section 459 (Pl. 10) indicate reef, probably fore-reef.* E. C. Druce (BMR, pers. comm.) found 6 species of well preserved reworked Lower Ordovician conodonts at locality 459/150.

The last outcrops of Cockatoo Formation to be described in the platform carbonate province are from the northwest extremity of the basin, in the Cone Hill and Shakespeare Hill area (Fig. 29; Pl. 14, figs 1 & 2). Numerous faults, most with a northwesterly trend, cross the area. With the exception of Cone Hill, all the outcrops contain uniform sequences of generally white cross-bedded quartz sandstone which is silicified near faults. A pebble bed, 10 feet thick, was found at locality 130/2. About 800 feet of quartz sandstone were measured at locality 130 on Shakespeare Hill. All the outcrops are tentatively regarded as Kellys Knob Member.

At Cone Hill, a poorly exposed subhorizontal sequence, possibly 100 feet thick, of yellow quartz sandstone and sandy limestone and marl is overlain by white quartz sandstone with layers of clay pellets. An indeterminate gastropod was collected from the sandy limestone. According to E. C. Druce (BMR, pers. comm.) limestone samples collected from this place do not contain conodonts. The calcareous beds possibly represent the top of the Westwood Member, and the overlying sandstone the Cecil Member.

Age of the Cockatoo Formation

By reference to superposition alone, the base of the Cockatoo Formation is younger than Lower Ordovician (the age of the youngest rocks in the underlying sequence); and the top of the formation is lowermost Famennian(toII) (the age of the base of the conformably overlying Ningbing Limestone and Buttons Beds) or slightly older.

---

* Veevers (BMR Bull. 109) reinterprets this outcrop as interfingering lagoonal and back-reef limestone.

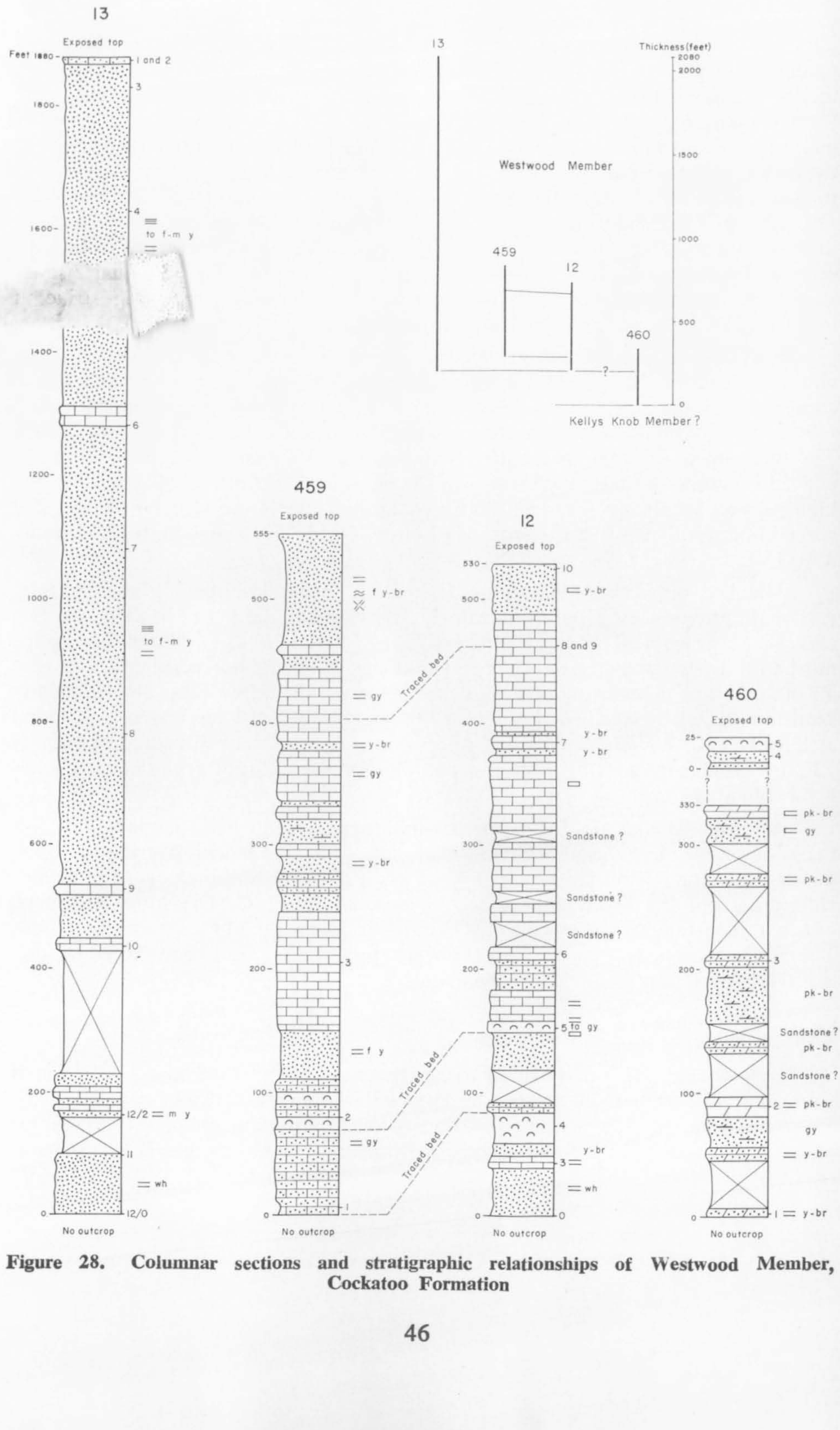


Figure 28. Columnar sections and stratigraphic relationships of Westwood Member, Cockatoo Formation

A preliminary account of the palaeontology and correlation of the Devonian formations of the Bonaparte Gulf Basin is given by Roberts, Jones, & Druce (1967). The Westwood, Hargreaves, and Kununurra Members of the Cockatoo Formation are the only members containing abundant fossils, and the conodonts, ostracods, and brachiopods indicate a general correlation with the Frasnian. Because these members are in the middle part of the formation, and because the Cockatoo Formation is overlain by Famennian(toII-toVI) limestone (Ningbing Limestone), the fossiliferous part of the Cockatoo Formation is thought to be approximately middle Frasnian (Figs 4 & 40). The lower part of the formation contains poorly preserved pelecypods and wood fragments (Roberts et al., 1967) and cannot be precisely dated; it is probably early Frasnian or late Givetian.

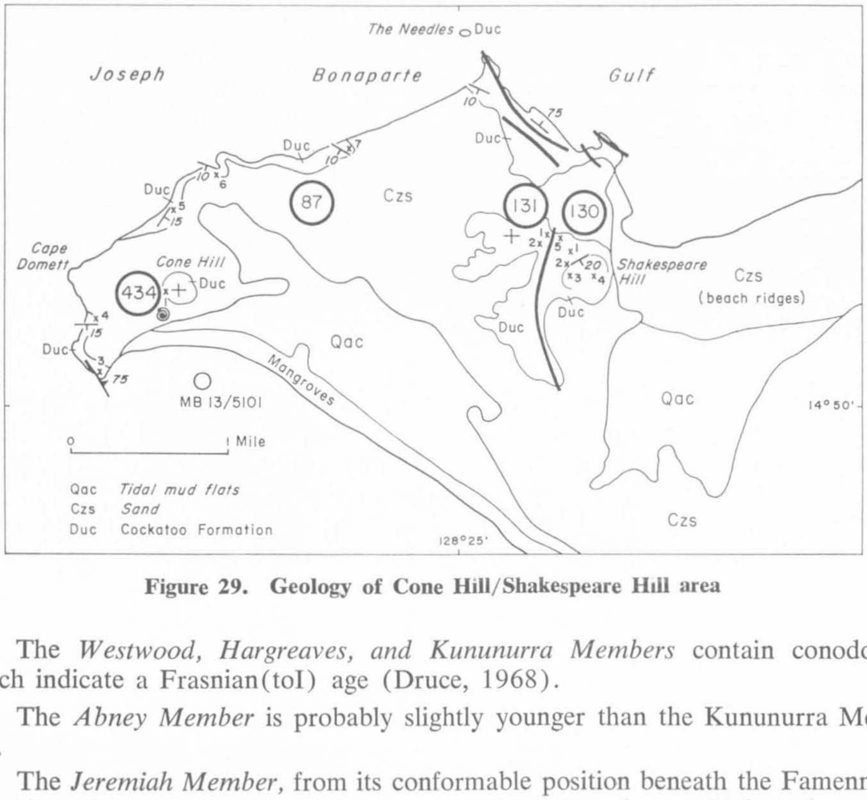


Figure 29. Geology of Cone Hill/Shakespeare Hill area

The *Westwood, Hargreaves, and Kununurra Members* contain conodonts which indicate a Frasnian(toI) age (Druce, 1968).

The *Abney Member* is probably slightly younger than the Kununurra Member.

The *Jeremiah Member,* from its conformable position beneath the Famennian Ningbing Limestone, is earliest Famennian or latest Frasnian, or both. The conodonts found in the type area of the Jeremiah Member (Fig. 26, locs 442/12 and 444/4) are apparently Tournaisian, but this is an anomalous age because at these localities the Jeremiah Member is overlain by Ningbing Limestone dated as Famennian on the basis of conodonts and brachiopods. This indicates that the conodonts in the Jeremiah Member have been introduced by a stratigraphic leak, or that they have been misidentified owing to poor preservation (E. C. Druce, BMR, pers. comm.).

The *Cecil Member,* lying beneath the Jeremiah Member and above the Westwood, Hargreaves, and Abney Members, is probably late Frasnian.

The *Kellys Knob Member* probably lies within the lower half of the Frasnian.

The age of the *Ragged Range Member* ranges from that of the Kununurra Member to older than the Kellys Knob Member, and thus spans at least the lower half of the Frasnian, and possibly extends into the Middle Devonian.

PALAEONTOLOGY

The fossils of the middle part of the formation increase in number both of species and of individuals from a minimum in the Kununurra Member, near the margin of the basin, through the Hargreaves Member to the Westwood Member, which is farthest from the southern margin. Many groups in the Westwood Member (algae, corals, ostracods, and stromatoporoids) are not found in the equivalent members. This seems to be a clear indication of the adverse influence of terrigenous deposition on these organisms in the conglomeratic province. Pelecypods, in contrast, were able to live on or in the quartz sand, but are nowhere abundant in the sandstone of the conglomeratic province.

This horizontal variation in ecology is matched by even sharper vertical variation. In places, the products of coarse terrigenous deposition (Kellys Knob Member, Cecil Member, and even conglomerate in the Ragged Range Member) contain pelecypods, but nowhere are they abundant. Fish plates are also scattered through the Cecil Member. Even near the margin of the basin, the vertical contrast in fossil content is marked, for example, between the Kununurra Member and the other conglomeratic members in the type section of the Cockatoo Formation across Matheson Ridge. The Jeremiah Member also contrasts with the Cecil Member in its relatively high fossil content.

Plants (mostly *Leptophloeum*) have been found in the Ragged Range, Kellys Knob, Kununurra, Hargreaves, Westwood, Jeremiah, and Cecil Members. Their distribution seems to be independent of the distance from the margin of the basin.

SEDIMENTOLOGY

The terrigenous component of the Cockatoo Formation is almost entirely quartz or quartzite, and indicates an overwhelming concentration of these materials in the source area; any material finer than sand was almost completely separated in the platform province (except during the deposition of the Kununurra, Hargreaves, and Westwood Members), and deposited elsewhere. That the sand was intensely worked by water is evident from the ubiquitous cross-bedding. The description of cross-bedding and other sedimentary structures, an analysis of directional structures, and a description of the rocks, will be made in a subsequent report (Veevers, BMR Bull. 109, in prep.).

Depositional Environment

With one known possible exception, the entire Cockatoo Formation was deposited in water: the exception is the sandstone with very thick sets of cross-beds at and near locality 239A-C (Fig. 19), whose cross-bedding is being further analysed. The evidence so far is inconclusive and indicates deposition by either wind or water.

The fish plates and plants do not help in determining whether the formation was laid down in fresh or salt water. The only other fossils found outside the indubitably marine middle part of the formation are pelecypods, and because the pelecypods are commonly associated with marine fossils in other parts of the formation, they too are taken to indicate marine deposition.

The abundant algae, including stromatolites and oncolites, in the limestone of the Westwood Member indicate deposition in very shallow (and probably clear) water. The only other fossils in the Cockatoo Formation indicate nothing more precise than the neritic zone. The ubiquitous trough and planar cross-bedding in the Kellys Knob and Cecil Members indicates shallow rather than deep neritic deposition.

The build-up of algae and corals in the fore-reef of the Westwood Member possibly indicates deposition in warm to warm-temperate water.

Summary

The Cockatoo Formation was probably deposited in a uniformly shallow to very shallow warm sea; the horizontal and vertical variations in the formation can be attributed to changes in the provenance area and not to differences in the environment of deposition. Uplift of the Pincombe Inlier and of the land bordering the eastern margin of the basin, probably by step faulting and block faulting, caused conglomerate (Ragged Range Member) to be deposited close to the shore, and sandstone (Kellys Knob Member) offshore. As the influence of these movements waned, by lowering of the source by erosion, and the supply of terrigenous sand decreased, deposition of very fine sand, silt, and carbonate sediment became dominant (Kununurra, Hargreaves, and Westwood Members), culminating in the deposition of a reef at Westwood Creek. A repetition of this cycle, by renewed uplift of land along the eastern margin of the basin, but not by uplift of the Pincombe Inlier, produced the Cecil and Jeremiah Members.

According to this depositional model, the Cockatoo Formation is the product of two cycles of uplift and erosion of the land bordering a uniformly shallow warm sea. Subsidence of the sea floor kept pace with the deposition of 5,000 feet of sediment which, by comparison with Frasnian sequences elsewhere in the world, accumulated rapidly.

Famennian

The Famennian Ningbing Limestone and the equivalent Buttons Beds succeed the Cockatoo Formation with little or no hiatus, and together these three units make up the Upper Devonian succession of the platform province. In the basinal shale province, the Upper Devonian (Famennian and probably Frasnian) is represented by the lowest parts of the Bonaparte Beds in the Bonaparte No. 1 and Kulshill No. 1 wells. Because of its extensive outcrop, the Ningbing Limestone is the best known of the three Famennian units, and it is described first.

Ningbing Limestone (new name)

The Ningbing Limestone is here defined as the belt of limestone that crops out between the northwestern part of the Pincombe Range and a point 3 miles north-northwest of Knob Peak (Map 1). Most of the outcrop lies within the Ningbing Range, and almost all the rest in the Jeremiah Hills. The Ningbing Limestone conformably overlies the Jeremiah Member of the Cockatoo Formation, and is unconformably overlain by, or faulted against, Visean Utting Calcarenite or

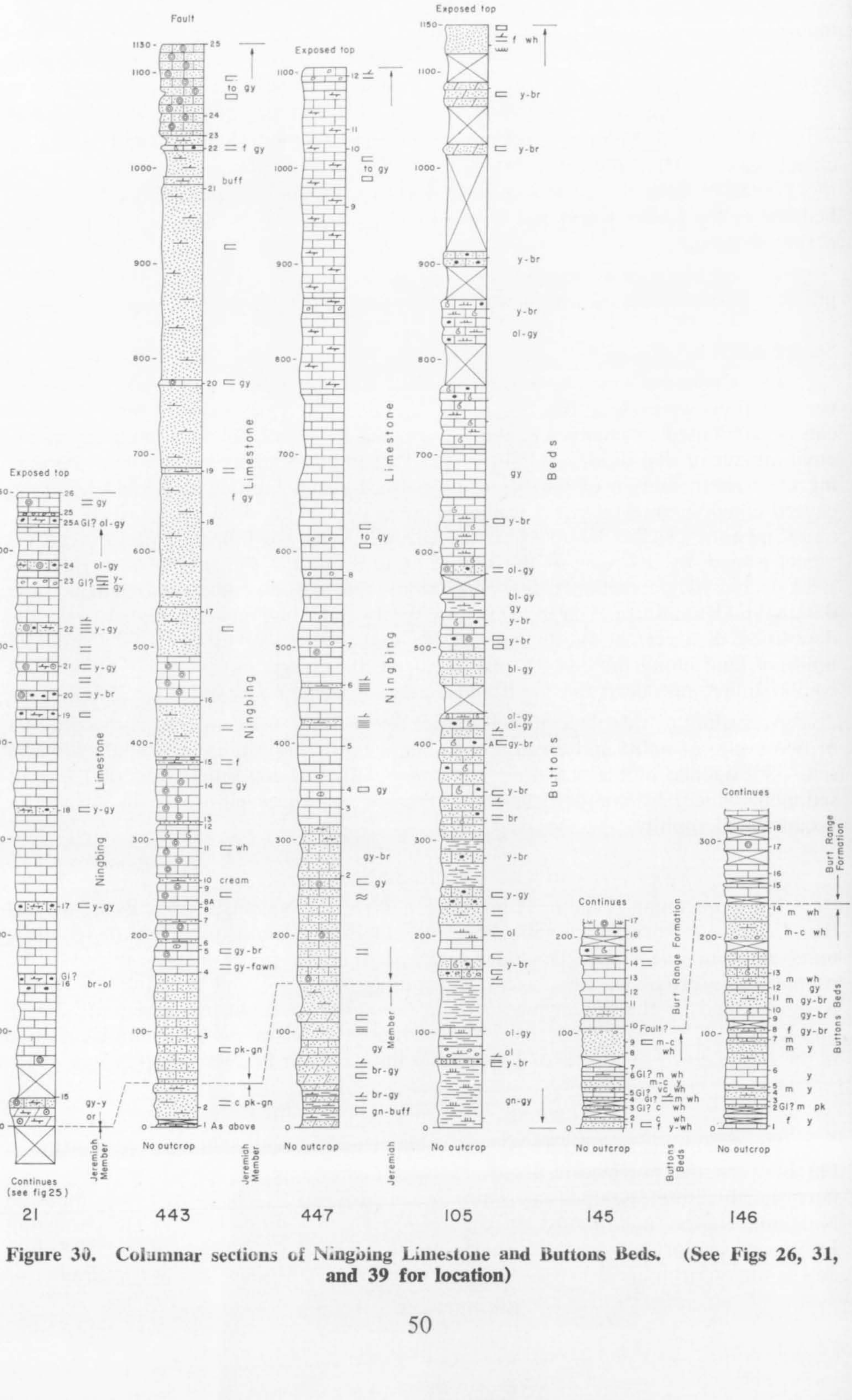


Figure 30. Columnar sections of Ningbing Limestone and Buttons Beds. (See Figs 26, 31, and 39 for location)

Burvill Beds. The uppermost 660 feet of section 21 (Fig. 30), at the south-western corner of the Ningbing Range (Fig. 31), is designated as the type section. The co-ordinates of the top of section 21 are latitude 15°18′S., longitude 128°37½′E. Section 443 in the Jeremiah Hills, 1,085 feet thick, is the thickest measured section.

The Ningbing Limestone is a reef complex in which four facies are recognized —reef, fore-reef, back-reef, and inter-reef. The back-reef predominates in outcrop.

Previous Work

Until recently, the Ningbing Limestone was regarded as part of the Burt Range Formation.

The first published reference was by Reeves (1951, pp. 2449-50), who briefly noted the 'stromatoporoid reefs' near Ningbing homestead. In his earlier, unpublished, report, Reeves (1948) gave some details, such as an estimated thickness of 500 feet of limestone near Ningbing, dated it as possibly Upper Devonian Stage IV, and alluded to the stromatoporoid reefs. He noted the structure of minor domes and basins, which he considered to be associated with the stromatoporoid reefs.

Noakes et al. (1952) did not mention the limestone at Ningbing.

Traves (1955) mapped the Burt Range Limestone, in which he included the Ningbing outcrops, and briefly described the outcrops south of Ningbing, and between Ningbing and Surprise Creek. He briefly referred to the reefs, which he called bioherms, and associated fossiliferous biostromal limestone which dips away from the reefs; like Reeves, he supplied few details.

E. P. Utting (pers. comm.) mapped the Ningbing Limestone in some detail; he pointed out the likelihood that the limestone is a reef complex, but found no indisputable evidence. Nor did Veevers et al. (1964), who continued to identify the limestone as the Burt Range Formation, which by this time was dated as Lower Carboniferous.

It was not until 1966 that Playford et al. demonstrated unequivocally that the Ningbing Limestone was a reef complex, and Jones & Druce (1966) that it was Famennian, both confirming what Reeves had said at the outset.

The 15-year delay between Reeves' (1951) bald assertion that the limestone at Ningbing was, at least in part, a Famennian reef complex, and confirmation in 1966, is largely attributable to its complexity and to the difficulty of access to the limestone outcrop, which consists of sharp rugged knobs deeply dissected by ravines and grass-covered pediments, surrounded by plains of deeply cracked black soil (Pl. 15).

Back-Reef

Not only is the back-reef (Pl. 16, fig. 1) the only widely exposed facies; it is also the only one in which sections thicker than 100 feet can be measured. Hence by default of the other facies, the back-reef contains the type section, which is designated as the uppermost 660 feet of section 21 (Figs 30 & 31), situated 6 miles west-southwest of Ningbing homestead. It consists of uniformly medium-bedded fairly pure grey to yellow limestone and minor dolomite, in which micrite-grain calcarenite is predominant. Except near the base, the outcrop is continuous.

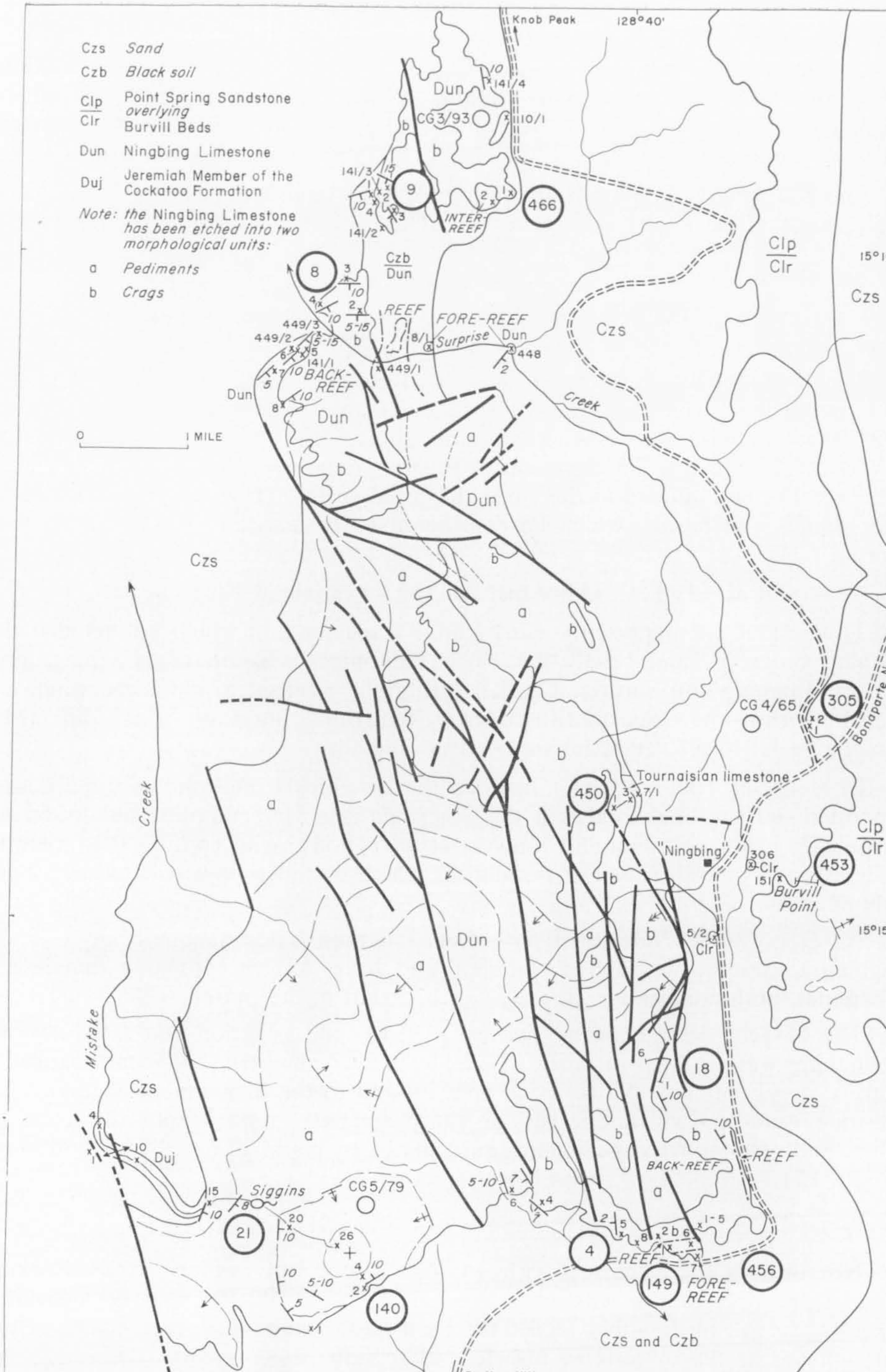


Figure 31. Geology of southern part of Ningbing Range. (Parts of map modified from photogeological map by R. Ruker and W. J. Perry.)

The base of the section is marked by the first extensive outcrop of grey to orange carbonate rock that overlies the poorly exposed Jeremiah Member of the Cockatoo Formation. This boundary is clearly visible on the air-photographs, both here and in the Jeremiah Hills. Elsewhere in the Ningbing Range, the base of the Ningbing Limestone is covered or faulted. The top of the type section is the youngest preserved bed in a small structural basin. This and other broad structures southwest of Ningbing homestead are well shown on the air-photographs.

Micrite-grain calcarenite is the main type of carbonate rock in this section. A 1-foot bed of limestone conglomerate with rounded pebbles and cobbles of dolomite, vein quartz, quartzite, and coralline algae (*Parachaetetes*) is found near the top (Pl. 16, fig. 2). (For further petrographic descriptions see Veevers (BMR Bull. 109, in prep.).)

Fossils in the type section are abundant, and are dominated by calcareous and porostrome algae. Most of the porostromes (*Girvanella*) are in the form of oncoliths, and the calcareous algae are fragmented and rolled masses of *Parachaetetes*. Crinoid ossicles, brachiopods, bryozoans, ostracods, and *Umbella* are also common. Few of these fossils provide a precise means of correlation, and ostracods and conodonts in other sections are the only reliable fossils for dating the limestone. E. C. Druce (BMR, pers. comm.) found reworked Ordovician conodonts at localities 140/5 and 141/5.

In Figure 31, the back-reef, which constitutes almost the entire outcrop, is mapped in two units on the basis of its morphology as seen on the air-photographs (Pl. 15). *Unit a* is a pediment or rock surface, indicated on the air-photographs by its uniformly layered light grey pattern, and *unit b* consists of crags, tens to hundreds of feet high, which on the air-photographs are dark grey to black, and appear to be massive. On the air-photographs, the two morphological units may mislead the observer into interpreting them as reef (unit b) and back-reef (unit a). This interpretation is quickly disproved by inspection on the ground: in all respects except morphology, the rock in the crags is identical with that in the pediment; that is, it is a medium-bedded mainly micrite-grain calcarenite. The erosion of the Ningbing Limestone into pediments and crags seems therefore to be caused solely by morphological processes*.

The back-reef is exposed in pediments and crags in a gorge cut by Surprise Creek through the Ningbing Range. On the western side of the range (locs 449/2, and 8/5-8), medium-bedded oncolitic limestone has weathered to yield free specimens of brachiopods. In a crag immediately to the east, at locality 449/3, similar medium-bedded limestone contains stromatoporoids. Incidentally, unlike Reeves and Traves, we found very few stromatoporoids in the Ningbing Limestone. The crags at locality 9, 1½ miles to the north, contain medium-bedded oncolitic limestone.

Thicker sections of the Ningbing Limestone are found in the Jeremiah Hills, which include a group of several broad limestone hills, some 200 feet high and

---

* At localities 149 and 456, at the southeastern tip of the Ningbing Range, the reef crops out in crags; elsewhere in the range it crops out in pediments also. In fact, the reef is barely distinguishable from the other facies on the 1:50,000 air-photographs, and Reeves' identification of reefs from an aeroplane must be questioned.

a few miles across, 10 miles southwest of Point Spring. A map of the western part of Jeremiah Hills is shown in Figure 26. This area is broken into blocks by faults which are clearly visible on the air-photographs. In nearly all the blocks, the dip is northerly and, except at faults, is not known to exceed 15°. The morphological division of the area into pediments and crags is not so clearcut as in the Ningbing Range, and has not been mapped. All the Ningbing Limestone mapped in Figure 26 is back-reef. Section 443 (Fig. 30) contains 1,085 feet of Ningbing Limestone between the Jeremiah Member of the Cockatoo Formation at the base and a fault at the top. Almost half the section is dolomitic, and section 447, which contains less dolomite, provides better material for description. This section is 950 feet thick between the Jeremiah Member and the exposed top. Section 447 consists mainly of sandy oncolitic limestone, birdseye limestone, *Stromatactis* limestone, and, towards the top, dolomitic limestone. Brachiopods and crinoid ossicles are common throughout, and calcareous algae, colonial corals, and stromatoporoids are also common in the uppermost 200 feet. Rare rounded pebbles and cobbles of vein quartz, quartzite, and sandstone, up to 4 inches across, were found in the upper half of the section. The only terrigenous pebbles found in section 443 are in a thin bed a few feet above locality 443/15.

Other outcrops of Ningbing Limestone to the southwest of Point Spring are shown in Figure 24. The outcrops at localities 422 and 423/2 are altered by faulting, and silicification is common. In contrast, the limestone at locality 424, only 1 mile from the outcropping Precambrian of the Pincombe Range, is unaltered, and consists of uniformly medium-bedded grey limestone with rare pebbles and cobbles of vein quartz.

Reef

The best exposed reefs in the Ningbing Limestone were found in the southern part of the Ningbing Range (Fig. 31). At localities 149 and 456 (Fig. 32), at the southeastern tip of the range, the reef (Pl. 17) is nearly a quarter of a mile wide; it consists of massive limestone that crops out in caverned pinnacles, and is flanked by thick-bedded back-reef limestone on the west, and by medium-bedded fore-reef limestone, including breccia, on the east. The reef consists of massive algal (*Renalcis*) limestone, 'reef tufa', stromatolitic limestone, *Stromatactis* limestone, and much recrystallized limestone and dolomite. Clusters of fossils, mainly brachiopods, occur in the limestone, and geopetal structures are common. On the ground, the outcrop of the reef in massive caverned pinnacles is diagnostic, but it is barely distinguishable from the other facies on the air-photographs.

The second well exposed reef was found at the eastern end of the gorge cut through the range by Surprise Creek (loc. 449/1). The reef consists of limestone with abundant intact masses of calcareous algae (*Parachaetetes*) as well as the rock types found at localities 149 and 456. The reef is exposed in a cliff 100 feet high, and is separated horizontally into two equal parts by 6 feet of medium-bedded back-reef limestone.

Reefs were also found intermittently along the eastern edge of the Ningbing Range; and the northernmost outcrop of the Ningbing Limestone at locality 11/3 (Map 1), 3 miles north-northwest of Knob Peak, is reef, as shown by abundant reef tufa. The reefs are not as well exposed as those in the southern part of the range, and their relationships with other facies are not clear. Locality 463 (Fig. 63), 1 mile southwest of Utting Gap, is a good example of such an area.

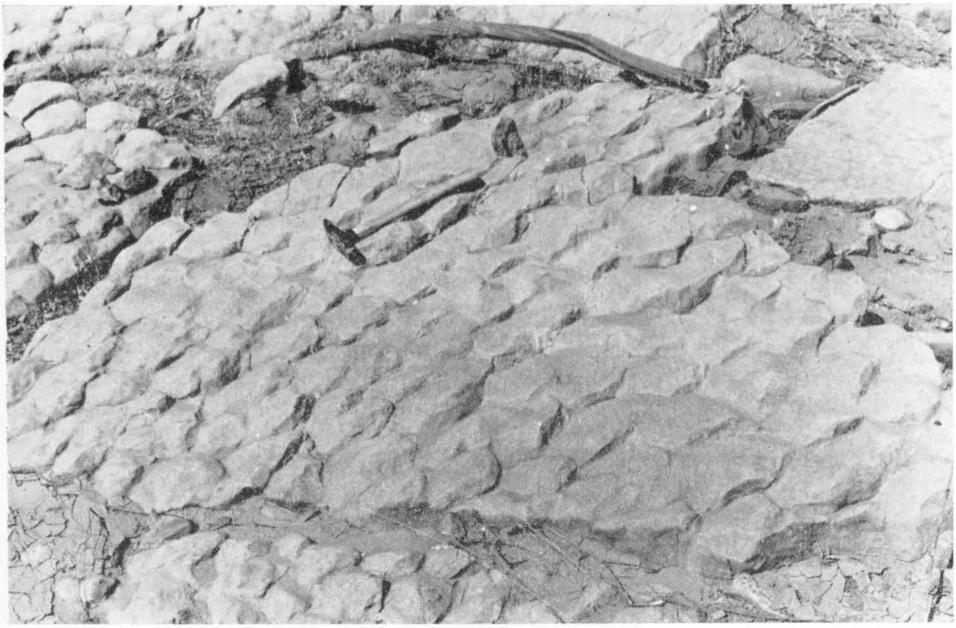


Plate 19, Figure 1. Polygonal cracks in calcarenite, about 525 feet above the base of the Buttons Beds at Buttons Crossing on the Ord River

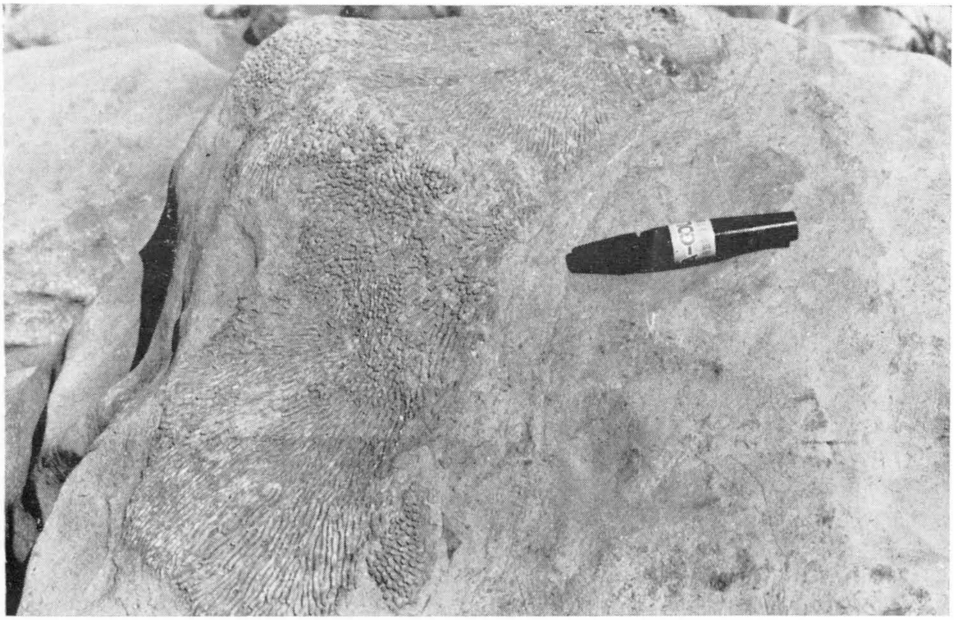


Plate 19, Figure 2. Colony of *Syringopora* in calcarenite, about 870 feet above the base of the Buttons Beds at Buttons Crossing on the Ord River. The scale is 4 inches (10 cm) long

Plate 20. Oblique air-photograph looking south at Mount Septimus, central Burt Range, and Enga Ridge. The banded pattern on the right is the Burt Range Formation

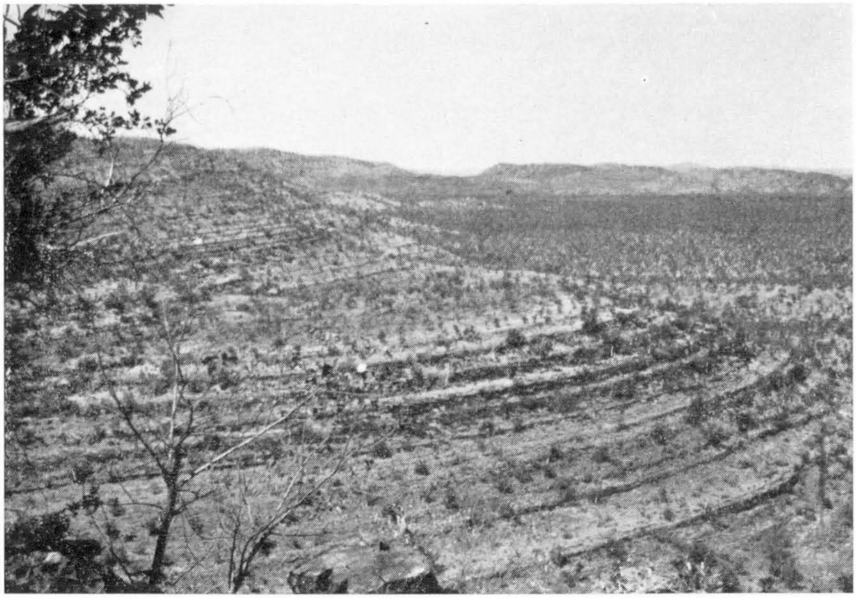


Plate 21, Figure 1. Looking south-southeast along Enga Ridge from the top of the scarp at section 103. The Burt Range Formation crops out as dark beds on the lower half of the hill, and is overlain at the break in slope by the Enga Sandstone. The hills in the background are Cockatoo Formation

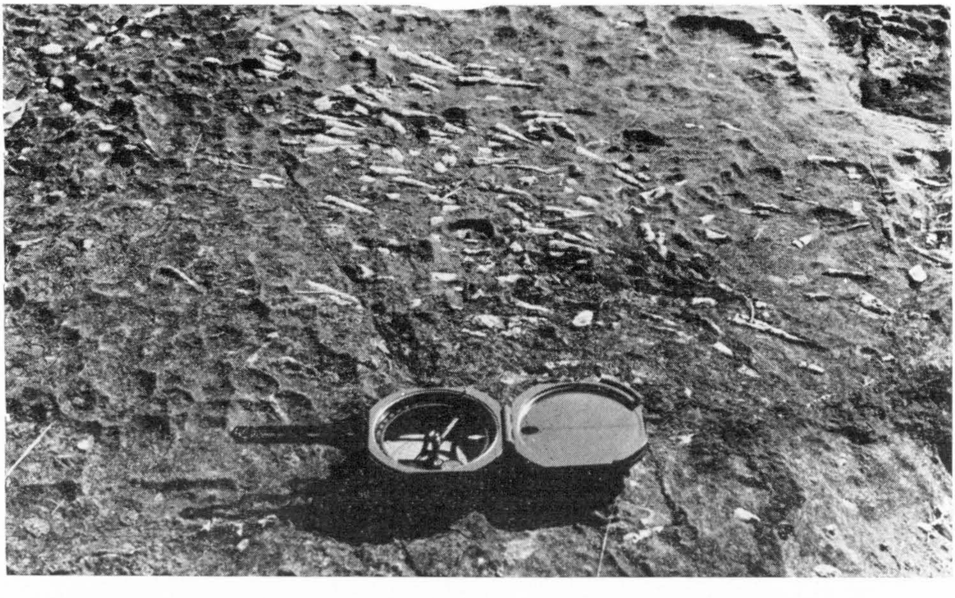


Plate 21, Figure 2. Straight nautiloids in a bed of sandy calcarenite at locality 101/2 in the Burt Range Formation. The nautiloids have been oriented by a current flowing from right to left

Plate 22. Vertical air-photograph (Auvergne Run 12, No. 5133) of Mount Septimus and the central Burt Range. The geology of the area is given in Figure 39. Compare with the oblique view in Plate 6 and Plate 21, figure 1

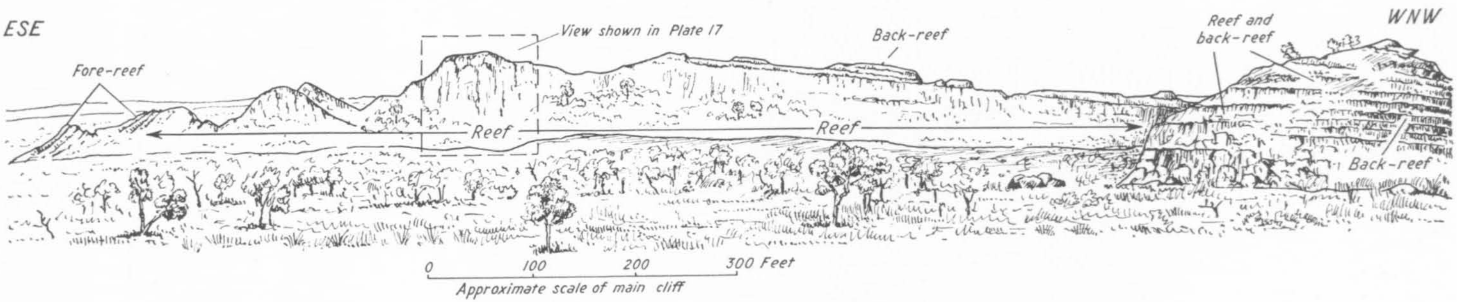


Figure 32. Panorama of reef complex in Ningbing Limestone, locality 456, 6 miles south of Ningbing homestead

At localities 463/1 and 2 the outcrops are probably back-reef; at localities 463/3 and 4, reef; at locality 463/5, fore-reef. The Ningbing Limestone west of locality 108 (Fig. 63) contains a narrow reef flanked by breccia on the east and by back-reef with tongues of reef on the west.

The minimum thickness of the reef can only be estimated by the height of the outcrops. The highest outcropping reef is at locality 456, where it is estimated to be 150 feet high.

Fore-Reef

The only place where fore-reef was seen next to the reef is the southeastern tip of the Ningbing Range (Figs 31 & 32, locs 149 & 456), where the fore-reef is a talus breccia which dips away from the reef at 20°; it consists of blocks of reef up to 6 feet long set in thin-bedded calcarenite. Fragments of stromatolites and calcareous algae are common in the calcarenite.

An isolated outcrop in the bed of Surprise Creek (loc. 448), 1 mile east of the exposed reef, consists of thick-bedded breccia which dips at 2° to the southeast. Geopetal structures, *Renalcis,* and *Stromatactis* are common in the matrix. Ten miles to the north and 2 miles north of Tanmurra Creek, an isolated outcrop (loc. 17/4, Pl. 18, figs 1 & 2) of medium-bedded pebble to boulder fore-reef conglomerate contains angular to rounded fragments of limestone up to 12 inches wide. The conglomerate dips at 15° to the east.

Inter-Reef

The outcrops of platy grey and pink sandy pisolitic limestone at localities 455/1 and 3 (Fig. 33) are interpreted as inter-reef. The limestone contains the same brachiopods as those in the nearby reef (loc. 455/2). The inter-reef limestone dips at 30° away from the reef.

Locality 466/2, 1½ miles north of Tanmurra Creek, was the only other place where inter-reef was found and, as at localities 455/1 and 3, it consists of platy sandy limestone with brachiopods.

Tournaisian Limestone Near Ningbing Homestead

E. P. Utting (pers. comm.) discovered richly fossiliferous limestone at a locality near Ningbing homestead, which we later visited and called locality 7/1 (Fig. 31). The fossiliferous limestone lies at the eastern edge of the limestone outcrop of the southern Ningbing Range, and is apparently continuous with it. The brachiopods and conodonts at locality 7/1, however, indicate correlation with localities 100/23-25, 685 to 815 feet above the base of the type section of the Burt Range Formation, or middle Tournaisian (upper part of the K Zone of England (see Druce, 1968)).

Locality 7/1 is part of the limestone pediment, and consists of massive recrystallized limestone with very large *Stromatactis,* and clusters of brachiopods with rare trilobites in a matrix that contains conodonts. Except for its fossils, this limestone is indistinguishable from the reef limestone of the Ningbing Limestone.

The field relations of the massive limestone at locality 7/1 to the adjoining limestones are obscure because of poor outcrop; the structure is also obscure on the air-photographs.

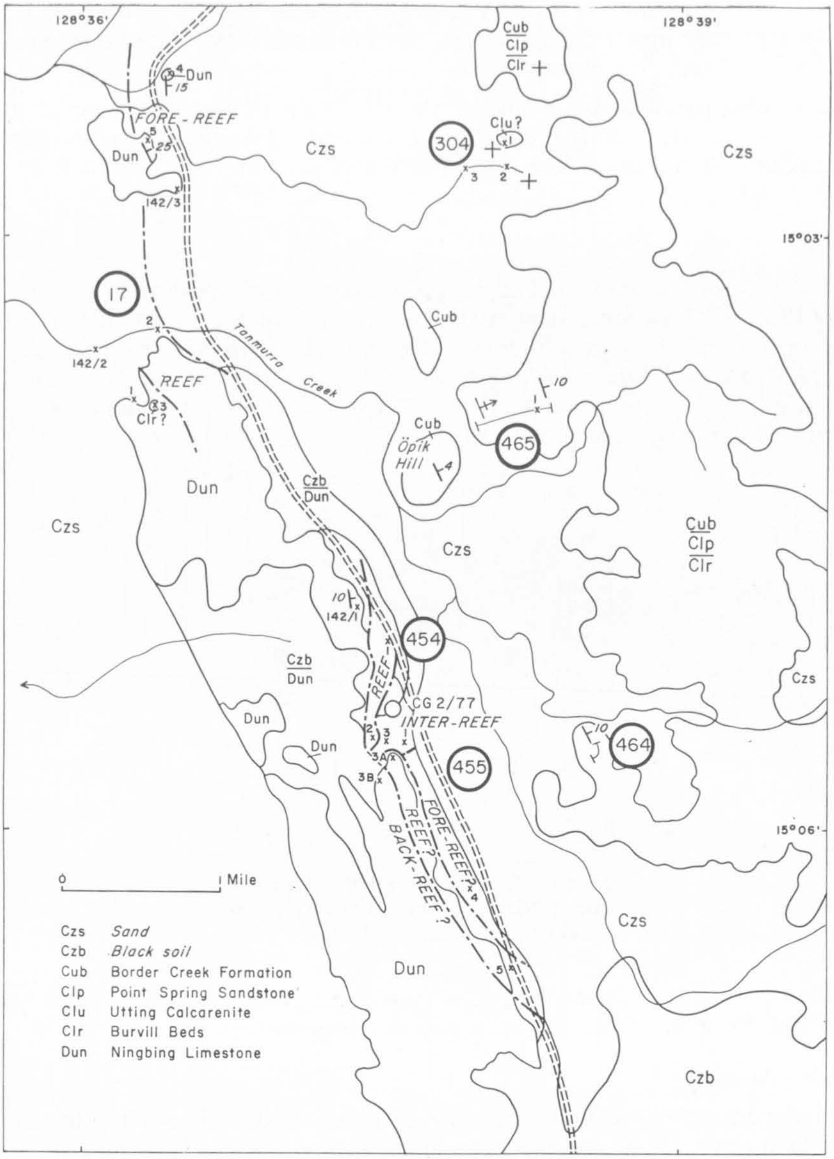


Figure 33. Geology of Öpik Hill area

We have assumed (Fig. 34) that the limestone at locality 7/1 is the youngest known of the Ningbing reef complex: this interpretation is supported by the close resemblance of the limestone to the Famennian reef limestone, which suggests continuous reef deposition. But it is also possible that it unconformably overlies the Ningbing Limestone. At locality 210/6, on the northern edge of the Pretlove Hills, Tournaisian breccia, which is slightly younger than the limestone at locality 7/1, unconformably overlies the Cockatoo Formation, and indicates a Tournaisian marine transgression in this area (Veevers & Roberts, 1966). However, it seems unlikely that reef limestone similar to the Famennian reef limestone would re-establish itself above an unconformity.

It is also possible, but unlikely, that the bulk of the limestone at locality 7/1 is Famennian, and the clusters of brachiopods and conodonts represent Tournaisian infillings of cavities which were deposited during a Tournaisian transgression.

Age

The palaeontology of the Ningbing Limestone has been described by Roberts et al. (1967). Conodonts suggest that most zones of the Famennian are represented in the reef complex, although as yet no conodonts of toIV age have been recovered. Jones & Druce (1966) had earlier suggested that the Ningbing Limestone was early Famennian (upper toII$_{\beta}$-lower toIII$_{\alpha}$), but conodonts of younger Famennian ages have since been found.

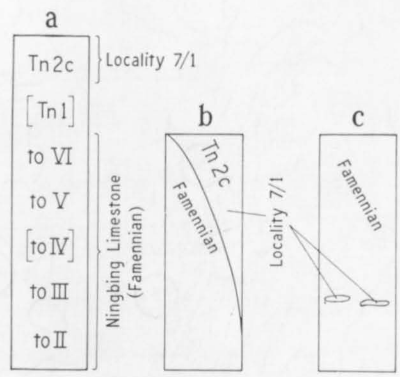


Figure 34. Possible relationships between Ningbing Limestone and Tournaisian limestone at locality 7/1

The conodont evidence suggests that there was continuous reef growth throughout the Famennian and even into the Tournaisian.

Overlying Strata

The boundary between the Ningbing Limestone and the overlying strata is only known to be exposed at one locality—locality 17/3 (Fig. 33), half a mile south of Tanmurra Creek, where 10 feet of white silicified quartz sandstone in tumbled blocks unconformably rests on the Ningbing Limestone. The sandstone overlies the limestone in a valley, indicating that much of the limestone, at least in the immediate vicinity, has been recently exhumed. The overlying sandstone is barren; it is probably part of the basal transgressive beds of the Visean, and has been tentatively mapped as Burvill Beds. The only other contact seen was at locality 108 (Fig. 63), where it is probably faulted. Near Ningbing homestead (Fig. 31), Burvill Beds are exposed at locality 5/2, only a few hundred yards from the exposed eastern edge of the Ningbing Limestone; steep erratic dips in the Burvill Beds in this area indicate complex faulting.

Although the field relations are obscure, most of the evidence, including the regional geology, suggests that the Ningbing Limestone is unconformably overlain by the basal deposits of the Visean transgression, which are represented in the southern Ningbing Range area by the Burvill Beds.

Buttons Beds (new name)

The Buttons Beds are here defined as the Famennian sandy and silty lime stone that crops out in the bed of the Ord River north of Buttons Crossing (Fig. 35). The only other known outcrops are situated in the Eight Mile Creek area and in the Sorby Hills, and possibly at Spirit Hill. The Buttons Beds overlie, presumably conformably, the Jeremiah Member of the Cockatoo Formation, except at Sorby Hills, where they rest unconformably on Precambrian siltstone. On the Ord River, the top of the Buttons Beds is faulted, and in the Eight Mile Creek area and at Spirit Hill the beds are unconformably overlain by the Burt Range Formation. The top is eroded in the Sorby Hills. Section 105 (Fig. 30) on the Ord River is designated as the type section. The co-ordinates of the base of the type section are latitude 15°38′S., longitude 128°42′E. The Buttons Beds are equivalent to at least part, probably the lower part, of the Ningbing Limestone; contrary to earlier opinion (Playford et al., 1966), we regard them not as strictly part of the Ningbing Limestone reef complex, but as equivalent lagoonal deposits, between the shore and the reef complex.

Previous Work

Matheson & Teichert (1948, p. 84, pl. 11) mapped and described the outcropping limestone near Buttons Crossing as part of the Devonian Burt Range Series. According to them, Buttons Crossing is situated within the outcropping limestone; but the Ivanhoe 1-inch map published in 1944 shows Buttons Crossing a few miles to the south, as shown on Figure 35. Matheson & Teichert gave the total exposed thickness as about 1,000 feet, outlined the sequence of fossils, and referred the limestone to the middle part of the Upper Devonian, all of which we have confirmed. The 'cross-bedded brown sandstone' (Matheson & Teichert, p. 84) that crops out on the west bank downstream from the limestone is now known to be Cambrian Clark Sandstone. The 'small occurrence of limestone with *Syringopora,* rugose corals, and ostracods on the east bank' farther downstream was not seen, possibly because while we were there it was covered by alluvium. What outcrops were seen in this area are all Cambrian (Fig. 36, taken from Kaulback & Veevers, 1968) and their association with Devonian limestone indicates the structural complexity of the area.

Traves (1955, pl. 1, his loc. 10) showed only a small outcrop of limestone in the Ord River near its junction with Spring Creek (mistakenly called Buttons Crossing), and suggested that this is the southern extension of the limestone near Ningbing. His assertion that biohermal limestone was found at this locality has not been confirmed. A. A. Öpik (BMR) identified some of the fossils and pointed out that they bear a marked similarity to those from 5 miles west of Mount Septimus. Our detailed studies show that the correlation cannot be maintained: the Buttons Beds are Upper Devonian; the other fossils mentioned, from the Burt Range Formation, are Lower Carboniferous.

The poorly exposed Buttons Beds beneath the type section of the Burt Range Formation do not seem to have been recorded hitherto.

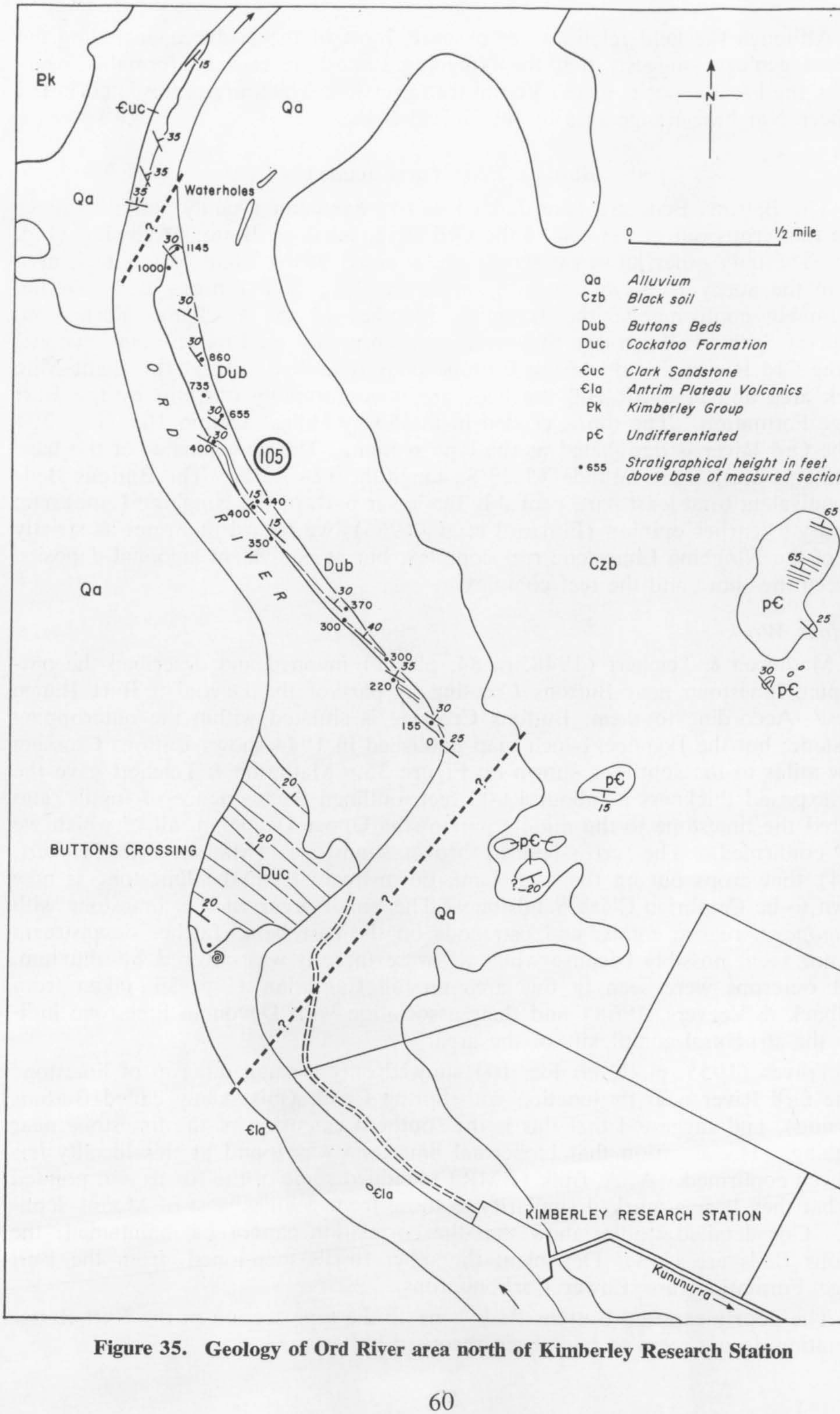


Figure 35. Geology of Ord River area north of Kimberley Research Station

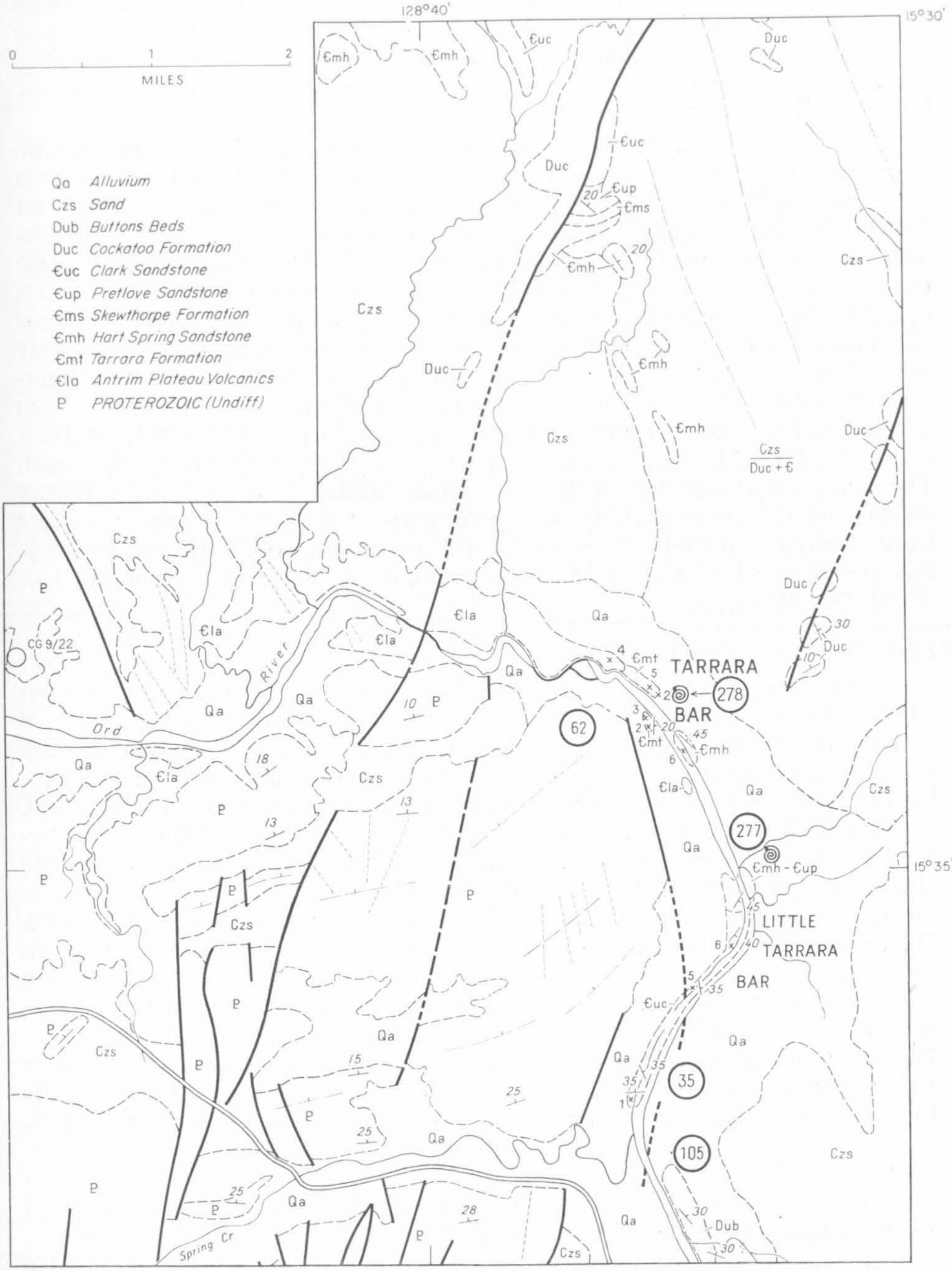


Figure 36. Geology of Tarrara Bar area, Ord River. (After Kaulback & Veevers, 1968)

Type Section North of Buttons Crossing (Figs 30, 35)

The type section (105) is probably conformable on the Cockatoo Formation at Buttons Crossing, but as mentioned on page 33, this is not certain because of the complex structure of this area. The top of the type section is marked by an inferred concealed fault, which brings the Cambrian Clark Sandstone and the Buttons Beds together.

The type section consists of silty micrite (0-65 ft), pebbly limestone with terrigenous fragments, including basalt (65-85 ft), sandy skeletal micrite-grain calcarenite, with interbedded calcareous sandstone and calcisiltite (85-1,015 ft) (see Pl. 19, fig. 1), sandy and silty dolomite (1,015-1,090 ft), and finally, feldspathic quartz sandstone (1,090-1,150 ft). Fossils are abundant, and include algae (porostromes, *Parachaetetes, Umbella*), bryozoans, brachiopods, conodonts, corals (Pl. 19, fig. 2), crinoid ossicles, fish plates, gastropods, ostracods, stromatoporoids, and plants (*Leptophloeum*). Of these, only the ostracods indicate detailed local correlation. According to Jones (1968), the ostracods in the interval 350 to 430 feet in the type section indicate correlation with locality 21/22 in the type section of the Ningbing Limestone, and with locality 100/4 in the Buttons Beds in the Eight Mile Creek area. Correlation by means of other fossils is general. The conodonts at 820 feet in the type section indicate Zones $toII_{\beta}$-III_{α} (Druce 1968), and the brachiopods from different parts of the type section all indicate Upper Devonian, probably Famennian. Hill (1954) described two coral species, *Palaeosmilia contexta* Hill and *Syringopora patula* Hinde, from the Buttons Beds of the Ord River.

Eight Mile Creek Area (Fig. 39)

Two poorly exposed sections of the Buttons Beds (Fig. 30, sections 145 & 146) were measured in the Eight Mile Creek area. Both sections are covered at the base, and are overlain by the Burt Range Formation. No structural break is visible at the upper boundary, either on the ground or on the air-photographs, but the fossils on either side show that the boundary is an hiatus. In section 146, the Buttons Beds are 125 feet thick and consist of sandy skeletal limestone interbedded with pebbly calcareous sandstone. In section 145, pebbly sandstone and glauconitic calcareous sandstone are the only types exposed. The pelecypods at locality 146/4 are similar to those found at locality 266, southeast of Spirit Hill. The common Upper Devonian assemblage of brachiopods, pelecypods, gastropods, and *Leptophloeum* is found in this section, and at locality 146/13, the association of the same stromatoporoids and calcareous algae as those in the upper limestones of section 105 indicates a similar depositional environment if not the same age. The only firm evidence for finer correlation is provided by the ostracods at locality 100/4 (Fig. 41), near the preserved top of the Buttons Beds, which according to Jones (1968) indicate correlation with the interval 350 to 430 feet in section 105.

Sorby Hills (Fig. 37)

The Sorby Hills are five small hills rising from the plain near the northeastern tip of the Pincombe Range. On the air-photographs the rocks have a well bedded pattern and soft grey tone which distinguishes them from the nearby Precambrian rocks.

The Sorby Hills consist of Buttons Beds which overlie, with slight angular discordance, Precambrian siltstone; and a downfaulted sliver of Burt Range Formation. The unconformity between the Buttons Beds and the Precambrian shows that this part of the Pincombe Inlier was above sea level immediately before the Buttons Beds were deposited. The contact between the sliver of Burt Range Formation and the Precambrian is not exposed and, apart from the sandy nature of the rocks in the fault sliver, there is no evidence to indicate whether the Pincombe Inlier persisted, at least intermittently, as a landmass into the Carboniferous.

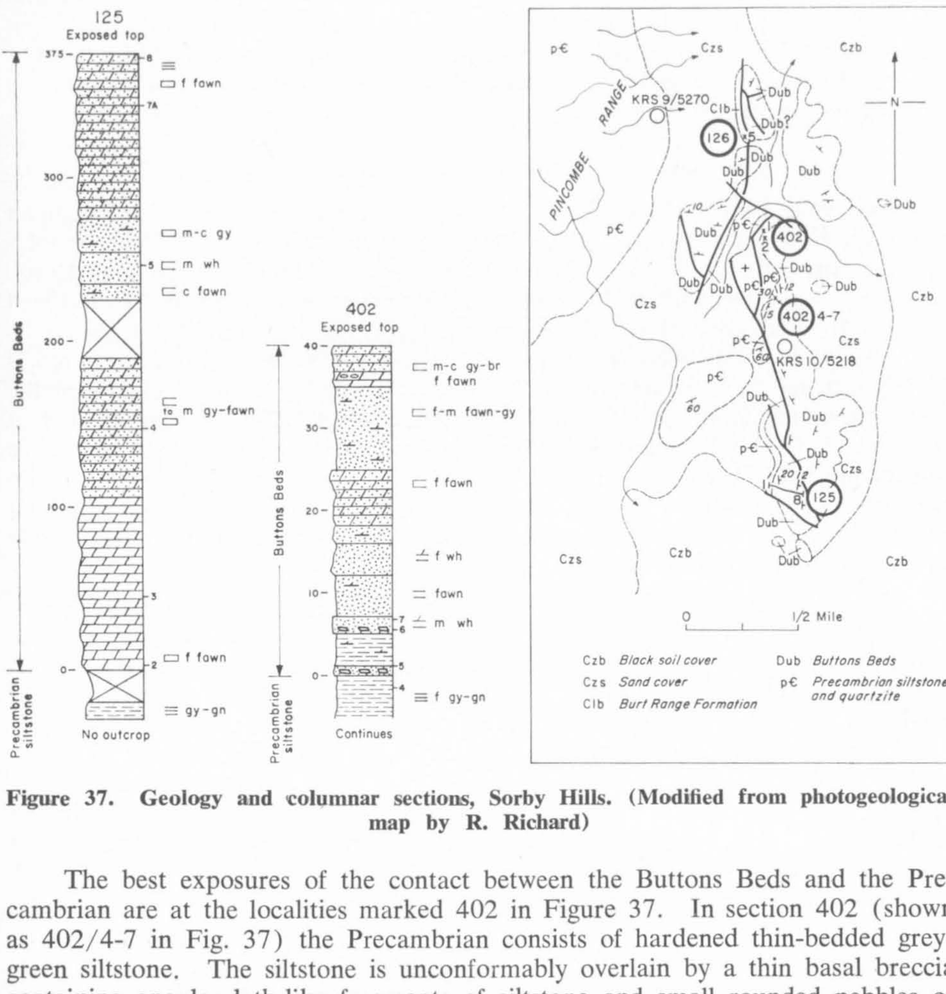


Figure 37. Geology and columnar sections, Sorby Hills. (Modified from photogeological map by R. Richard)

The best exposures of the contact between the Buttons Beds and the Precambrian are at the localities marked 402 in Figure 37. In section 402 (shown as 402/4-7 in Fig. 37) the Precambrian consists of hardened thin-bedded grey-green siltstone. The siltstone is unconformably overlain by a thin basal breccia containing angular lath-like fragments of siltstone and small rounded pebbles of milky quartz in a sandy matrix. A second similar breccia, slightly higher in the section, is followed by dolomitic sandstone and sandy dolomite. The only fossils collected from this part of the Buttons Beds come from locality 402/1, where indeterminate gastropods and an unidentified crinoid calyx were found in rubble beneath the lowermost outcrops of the formation.

In section 125, on the southern part of the same hill (Fig. 37), 375 feet of Buttons Beds rest with angular unconformity on Precambrian siltstone. The overlying rocks are mainly hard thickly-bedded fawn to grey sandy dolomite which becomes sandier in the middle and upper parts; a white quartz sandstone is present 250 feet above the base of the section. Conodonts from locality 125/4 indicate an Upper Devonian age of not older than Zone toIII and not younger than Zone toV. The only other fossils collected are poorly preserved indeterminate gastropods and pelecypods from locality 125/7A.

At locality 266, in the southeastern part of the Spirit Hill area (Fig. 53), pebbly quartz sandstone contains abundant *Leptophloeum australe* (M'Coy) and pelecypods which are the same as those from locality 146/4 (Fig. 39) near Eight Mile Creek. Half a mile to the north, the lower part of section 114 (Pl. 31) consists of barren white quartz sandstone overlain, probably unconformably, by the Burt Range Formation.

Upper Devonian Part of the Bonaparte Beds (Fig. 65)

Two wells, Bonaparte No. 1 and Kulshill No. 1, penetrate the Upper Devonian part of the Bonaparte Beds. Belford, Jones, & Roberts (*in* LeBlanc, 1964, unpubl.) date the cores in the interval 8,310 to 9,279 feet in Bonaparte No. 1 as Upper Devonian on the basis of fossils, principally the pelecypod *Buchiola*. In the well the oldest dated core above this interval is core 24 (6,616-20 ft), which is Tournaisian; no fossils were found in cores below 9,279 feet. The total depth is 10,530 feet and the lowest core 10,234 feet. On this basis, the thickness of the Upper Devonian in the well ranges from 969 feet (8,310-9,279) to 3,910 feet (6,620-10,530). What part of the Upper Devonian is represented in the well is not known, because *Buchiola* ranges through the entire Upper Devonian. However, because the section beneath the Tournaisian at 6,620 feet seems to be continuous, most if not all the Upper Devonian is probably Famennian. This interpretation is shown in Figure 10.

The estimated minimum thickness of Upper Devonian sediments, in the interval 8,310 to 9,279 feet, according to Le Blanc (1964) consists of some 750 feet of light to dark grey shale and siltstone with minor interbedded sandstone, underlain by some 220 feet of sandstone and siltstone with minor shale. The estimated maximum thickness, in the interval 6,620 to 10,530 feet, includes an additional 1,251 feet at the bottom of the well, which is distinctly sandier than the overlying section and includes 232 feet of varicoloured shale, and 1,690 feet of silty shale, siltstone, and siliceous sandstone. A dipmeter survey indicates a change in dip at 7,480 feet. The angular difference is a few degrees only; it may indicate an unconformity or slightly more intense flow of the deeper shale and siltstone. For further details, Le Blanc's description should be consulted.

The lowermost 2,076 feet (interval 12,340-14,416 ft) in Kulshill No. 1 (Duchemin & Creevey, 1966) is Devonian. The fossils in this interval, which is overlain by the upper part (Visean) of the Bonaparte Beds, are plants in core 39, which, according to Mary E. White (*in* Duchemin & Creevey), indicate Middle or Upper Devonian; conodonts in core 40, which E. C. Druce (BMR, pers. comm.) has identified as Famennian (toII-toIV, possibly Zone toIII or toIV); and more plants in core 43, which Mary E. White has determined as possibly Middle Devonian.

The upper half (interval 12,340-13,310 ft) of the Devonian section consists of an upper unit of black to red shale, light grey siltstone, occasional grey sandstone, and common thin limestone. The shale contains traces of marine fossils and common plants, and the limestone contains foraminifers, echinoids, algae, ostracods, and conodonts. The lower half (13,310-14,416 ft) consists of grey silicified sandstone with black to grey shale, minor grey siltstone, and occasional silty or sandy limestone. Plants are common in the shale, and echinoid and mollusc fragments are scattered throughout. Further details are given in Duchemin & Creevey (1966).

Summarized Geological History of the Famennian

The conglomeratic and carbonate platform provinces in which the Cockatoo Formation was deposited in the Frasnian are still recognizable in the Famennian (Fig. 10), if due allowance is made for the general shift from terrigenous to biogenous deposition. A third depositional province, the basinal shale province, is recognized, in which part or all of the lower third of the section cut in Bonaparte No. 1 and Kulshill No. 1 was deposited during the Famennian. The recognition of the basinal province completes the classical sequence of equivalent facies, from an inshore conglomeratic facies influenced by terrigenous deposition, a carbonate province of pure (reef) limestone, and an offshore basinal province of fine terrigenous sediment, mainly shale and siltstone.

Compared with the Frasnian, the Famennian was tectonically quiet, at least along the eastern margin of the basin. Perhaps Upper Devonian reef growth started in the Canning Basin, as suggested by Rattigan & Veevers (*in* Veevers & Wells, 1961), as a result of block-faulting of the floor of the basin which provided bathymetric conditions suitable for reefs. There is no direct evidence for or against this hypothesis in the Bonaparte Gulf Basin, but if it were so, the trend of the reef along the eastern edge of the Ningbing Range would indicate a major structural as well as bathymetric trend in the Famennian.

Most if not all of the sediments were deposited in sea water. The Ningbing Limestone was deposited in shallow, clear, and probably warm sea water. The rare terrigenous pebbles scattered through parts of the back-reef of the Ningbing Limestone were possibly rafted by *Leptophloeum* trunks and branches, which are common in the limestone. The rare conglomerate bed in the back-reef indicates a brief period of emergence.

The Buttons Beds in the Eight Mile Creek area received abundant quartz and quartzite pebbles from the eastern edge of the basin; 15 miles westward, the Buttons Beds near the exposed base contain only one bed with pebbles, some of which are basalt which was probably derived from nearby land, possibly from the Pincombe Inlier. The terrigenous material in the rest of the section is very fine. The Buttons Beds were also deposited in shallow and probably warm sea water which was turbid, and reef growth was inhibited.

Any sediment in the basinal province equivalent to the reef complex must be marine because the reef could not have grown unless it faced the open sea. This argument also implies that the basinal province was an area of deeper water. The fossils in the intervals 8,310 to 9,279 feet in Bonaparte No. 1 and 12,340 to 14,416 feet in Kulshill No. 1 show that at least this part of the section in the basinal province is marine.

Comparison with the Canning Basin

Playford et al. (1966) have pointed out the similarity of the Ningbing reef complex to parts of the Upper Devonian reef complex of the Canning Basin

(Playford & Lowry, 1967). The basinal facies of both basins are also similar. The intervals 3,557 to 7,504 feet in Wapet Frome Rocks No. 2 and 2,195 to 2,697 feet in Wapet Babrongan No. 1 consist of shale, siltstone, and minor sandstone, and parts of the intervals contain *Buchiola*. The beds are of the same facies and probably also of the same age as the lower interval in Bonaparte No. 1.

The marginal facies of the northern Canning Basin in the Famennian consists of conglomerate, which has no obvious representative in the Famennian of the Bonaparte Gulf Basin.

CARBONIFEROUS

The Carboniferous sediments can be subdivided into two units separated by an erosional unconformity. The Lower Carboniferous sediments represent the later half of a marine depositional episode that started in the Upper Devonian (Veevers & Roberts, 1967); the sediments are fairly thick and varied, and contain abundant marine fossils, which clearly indicate the environment of deposition and age of the beds. The Upper Carboniferous sediments represent the beginning of a second depositional episode, comprising freshwater, brackish, and marine sedimentation, which extends through the Permian and into the Lower Triassic. The Upper Carboniferous sediments are thin and monotonous, and contain indeterminate plants but no other fossils; so their precise age is uncertain.

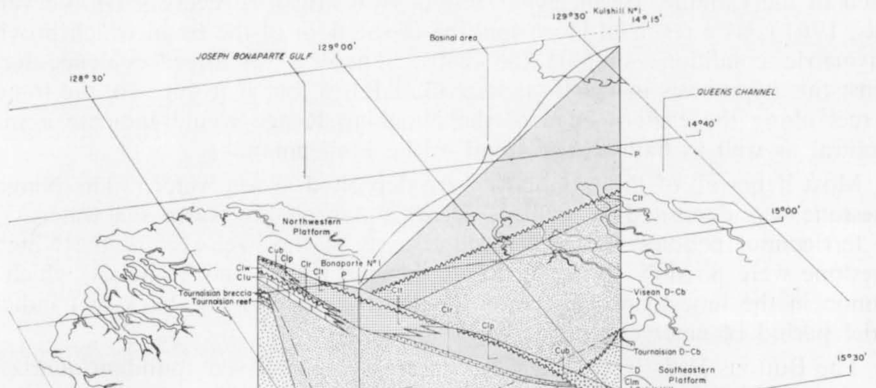


Figure 38. Distribution of Carboniferous formations in the Bonaparte Gulf Basin. (Looking N. 37° E.). (D) Devonian, (D-Cb) Bonaparte Beds, (Clb) Burt Range Formation, (Cle) Enga Sandstone, (Cls) Septimus Limestone, (Clz) Zimmermann Sandstone, (Clm) Milligans Beds, (Clu) Utting Calcarenite, (Clw) Waggon Creek Breccia, (Clr) Burvill Beds, (Clp) Point Spring Sandstone, (Clt) Tanmurra Formation, (Cub) Border Creek Formation, (P) Permian

In the Lower Carboniferous, as in the Upper Devonian, there were two main depositional provinces—the platform and basinal provinces (Fig. 38). Alternating quartz sandstone and carbonate rocks were deposited on the platform; the laterally equivalent dark siltstone and shale deposited in the basinal province are known from the subsurface only.

The exposed platform deposits are the only Upper Carboniferous sediments known in the basin.

Most of the Carboniferous terrigenous sediments were probably derived from Precambrian quartz sandstone, quartzite, shale, dolomite, basic volcanics, granite, and high-grade metamorphics. At times, the Lower Palaeozoic sandstone, dolomite, and basic volcanics, and the Devonian sandstone and limestone within the basin also contributed sediment.

The subdivisions of the platform sediments found in the Upper Devonian are not recognizable in the Lower Carboniferous. The Upper Devonian platform conglomeratic facies cannot be recognized in the Lower Carboniferous; and only a few of the Lower Carboniferous formations extend across the platform from the southeast to the northwest. The lack of continuity may be due to the emergence of the Pincombe Inlier.

The Carboniferous geology is therefore described by area rather than by province. The most complete and varied Lower Carboniferous sequence is exposed in the Burt Range area in the southeastern part of the platform.

Burt Range/Legune Area

Burt Range Formation

Almost all the outcrops of the Burt Range Formation are found in the southeastern and eastern parts of the Bonaparte Gulf Basin between the Pincombe Range and the margin of the basin, east of the Burt Range (Pl. 20). Smaller outcrops occur discontinuously along the eastern margin of the basin; they run in a northeasterly direction from Spirit Hill to Sandy Creek and on to Flapper Hill near Legune station (Map 1).

Matheson & Teichert (1948) used the name Burt Range Series for the limestone, calcareous sandstone, and sandstone cropping out between Eight Mile Creek and the western flank of the Burt Range.

Noakes et al. (1952) changed the name to Burt Range Limestone and separated the quartz sandstone at the top of the sequence, which Traves (1955) called the Enga Sandstone. Traves included the limestone at Ningbing and on the Ord River in the Burt Range Limestone.

In this Bulletin, following the usage of Utting (1958, unpubl.) and Hare et al. (1961, unpubl.), the name Burt Range Formation is substituted for Burt Range Limestone because of the presence of different rock types. The formation is further restricted by excluding the limestone at Ningbing, the limestone at Buttons Crossing on the Ord River, and the westernmost beds of limestone and calcareous sandstone exposed in a narrow belt 5 miles southeast of Martin Bluff (Fig. 39). The latter beds are mapped as Buttons Beds and are Famennian(toII-toIII); they are disconformably overlain by Carboniferous limestone of the Burt Range Formation. In the Burt Range area the break in sedimentation between the two carbon-

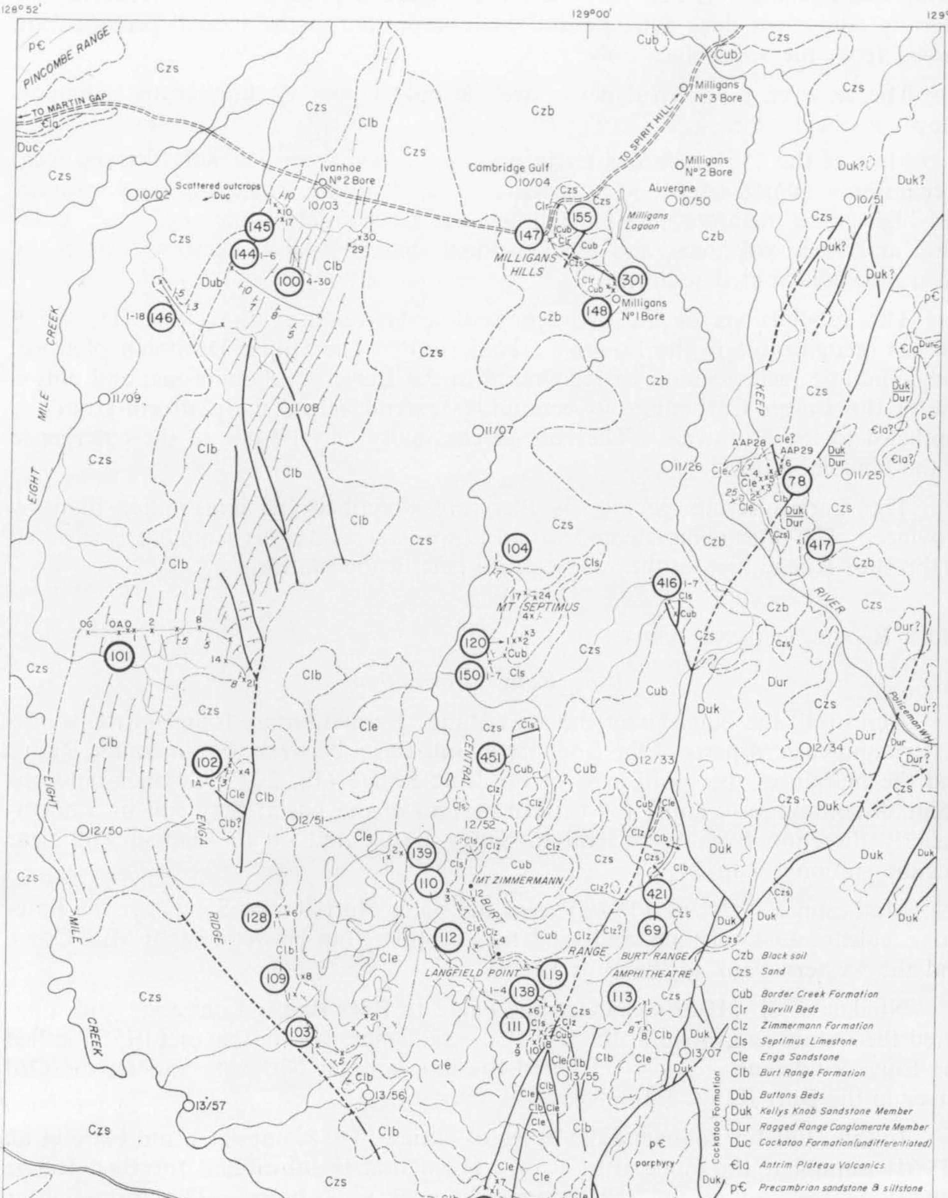


Figure 39. Geology of Burt Range area. (Modified from photogeological map by R. Richard)

ate sequences is equivalent to the upper half of the European Famennian Stage (Zones toIV, V, & VI) and also possibly the very basal part of the Carboniferous (Fig. 40).

Burt Range Area

The Burt Range Formation crops out on tree-covered plains and low ridges midway between Martin Gap and Mount Septimus, on the eastern side of Eight Mile Creek, and also along the steep western face of Enga Ridge (Fig. 39; Pl. 22).

The lower and middle parts of the formation form a low divide between Eight Mile Creek and an unnamed creek on the western side of Mount Septimus. On the air-photographs the outcrops have a striped pattern due to the alternating ribs of hard limestone and linear areas of soil (Pl. 20, right-hand side). The resistant rocks form prominent strike ridges which are interrupted by minor faults and are breached by subsequent tributaries of Eight Mile Creek. E. P. Utting (pers. comm.) believed the beds beneath the soil cover to be shale and shaly limestone, but the rocks on either side of sections 100 and 101 consist of slightly softer limestone than that forming the resistant ribs.

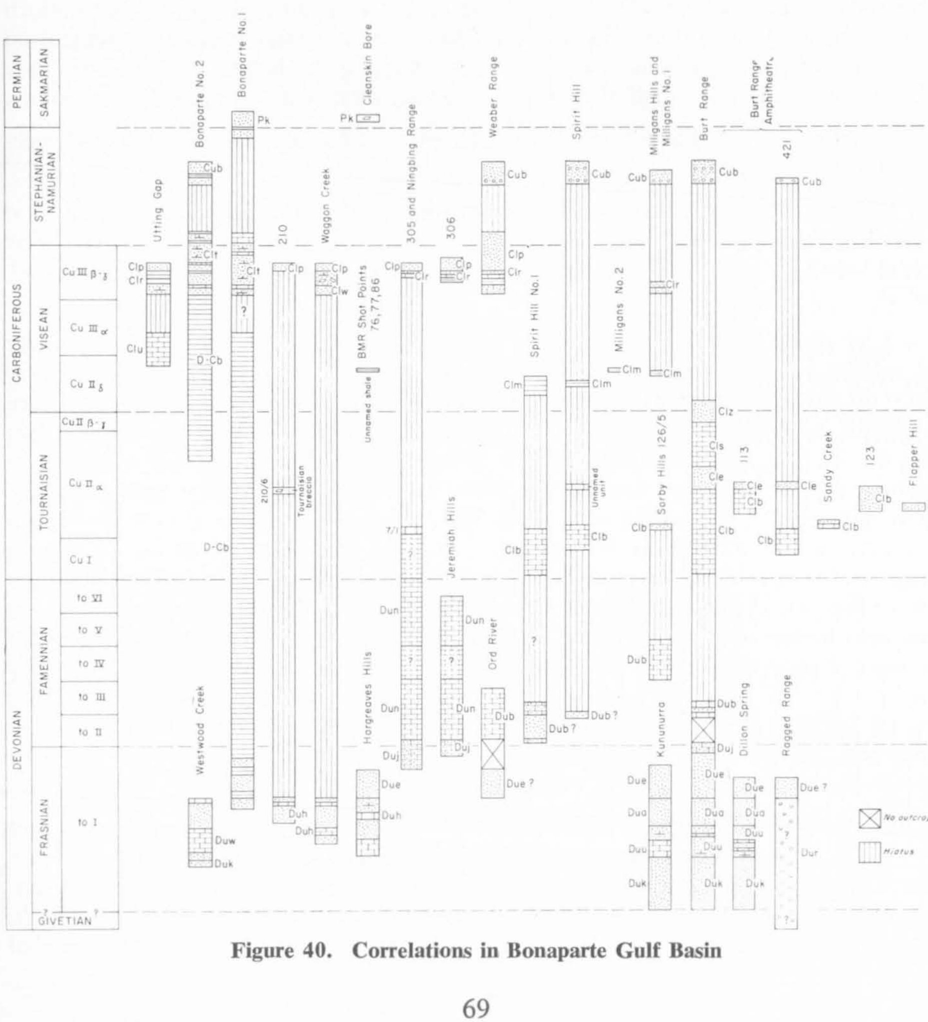


Figure 40. Correlations in Bonaparte Gulf Basin

The reason for the lack of major limestone outcrops to the south of section 101, in the area between the Matheson and Enga Ridges, is not clear. In an area of converging strike such as this (Pl. 6) dips should be higher and outcrops should be even more pronounced than those around the type section. However, there are virtually no outcrops of Burt Range limestone on the plain and only faint bedding patterns appear on the air-photographs. It is suggested that the formation becomes more sandy because it was deposited in a region of more clastic sedimentation nearer the shore, or that the Cainozoic sand cover derived from the hills to the south is much thicker than elsewhere.

To the north, the lower part of the formation extends into the Keep River plain, where it is covered by black soil and sand. Its apparent lensing out in this direction (Fig. 39) may be due to the sediments becoming more silty and even shaly towards the north.

The upper part of the formation crops out as regular benches below cliffs of Enga Sandstone on the western face of Enga Ridge (Pl. 21, fig. 1). Its resistance to erosion is at least partly due to the protection afforded by the cliffs. The rocks have a regular layered pattern on the air-photographs. In places the pattern is interrupted by masses of silicified sandstone and irregular areas of silicification along fault planes. The faults trend northwest along the length of the ridge; they generally have only a small throw and most of them can be regarded as joints.

Outcrops of the Burt Range Formation support Eucalyptus and yellow-flowering native cotton trees.

Seven stratigraphic sections have been measured in the Burt Range area; two in the lower and middle parts of the formation and five in the upper part. The section localities are shown in Figure 39 and the columnar sections in Figures 41 and 42.

Type Section. Until the present investigation little was known of the lower and middle parts of the Burt Range Formation. Section 100, measured 2 miles south of the track running between Martin Bluff and Milligans Lagoon, is here designated as the type section. The co-ordinates of the base of the section are latitude 15°38′S., longitude 128°55′E. The sequence disconformably overlies the Upper Devonian Buttons Beds and is 950 feet thick (Fig. 41); it comprises the lower and some of the middle part of the Burt Range Formation. The type section is complemented by section 101 in the lower and middle parts of the formation 6 miles to the south, and by section 103 in the upper part of the formation on Enga Ridge (Fig. 43). By using fossils to correlate between the three sections we have been able to establish a composite stratigraphic section, 1,510 feet thick, through the Burt Range Formation (Fig. 41); brachiopods and conodonts indicate that locality 100/13C is equivalent to locality 101/2, and locality 100/25 to locality 101/13. There could be a slight gap between the top of section 101 and the base of section 103 because of faulting, but the short-ranging brachiopods in both indicate that the break, if any, is very slight.

In the type section, the lowermost 150 feet consists of alternating hard and soft beds of thin-bedded olive-grey crinoidal calcarenite, with occasional sandy beds. A bed of stromatolitic limestone containing dome-shaped heads of *'Malacostroma concentricum'* Gurich, 1906, up to 2 feet in diameter and 9 inches high, is present 150 feet above the base of the formation. Finer-grained thin-bedded

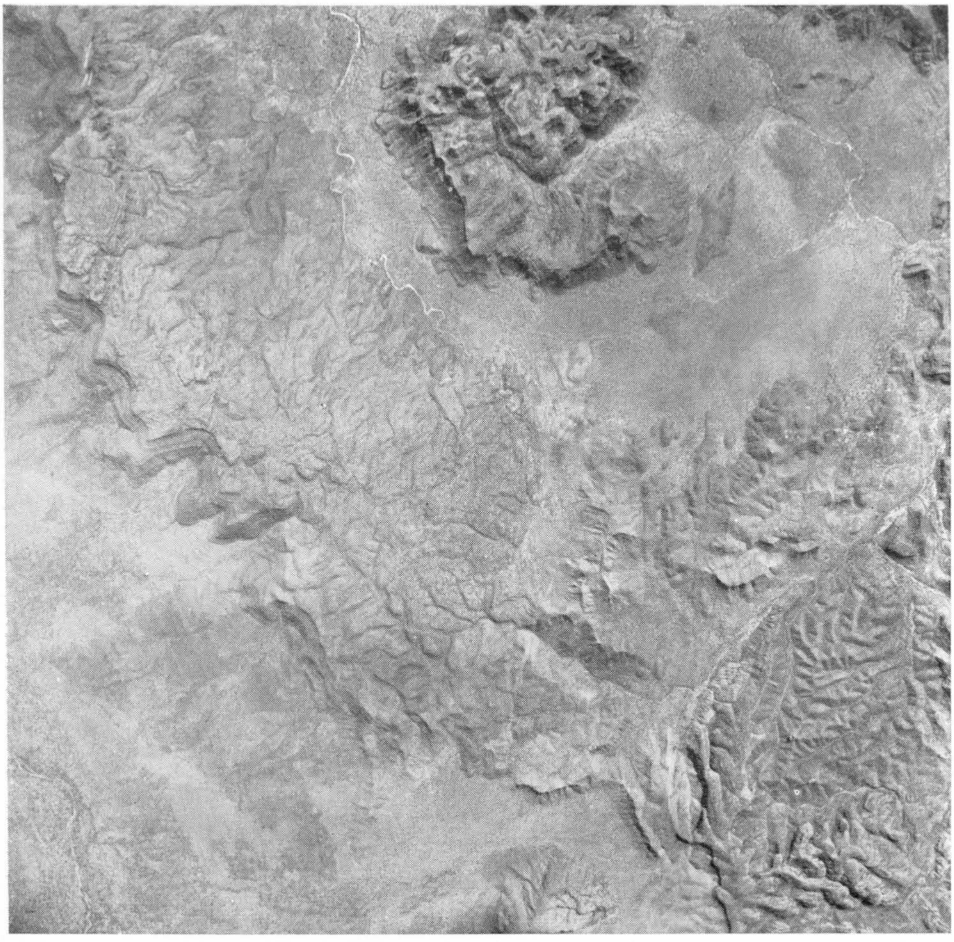


Plate 23. Vertical air-photograph (Auvergne Run 13 No. 5208) of the southern central Burt Range. The geology of the area is given in Figure 39. Compare with oblique aerial views in Plate 6 and Plate 21, figure 1

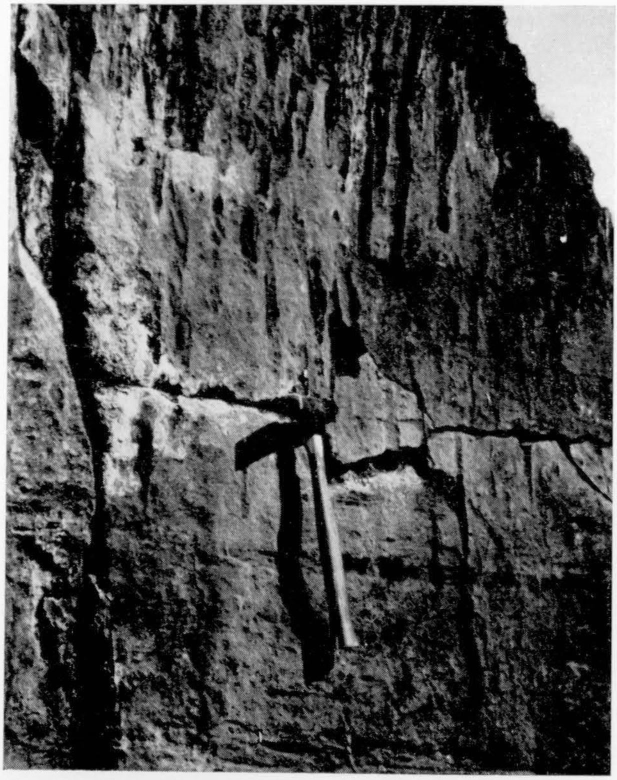


Plate 24, Figure 1. Vertical tubes in Enga Sandstone at section 102 at the northern end of Enga Ridge

Plate 24, Figure 2. A penecontemporaneous clast of thin-bedded calcarenite in crinoidal calcarenite at locality 104-12 in the type section of the Septimus Limestone at Mount Septimus. The scale is 6 inches (15 cm) long

Plate 25, Figure 1. A typical outcrop of thin-bedded calcarenite in the Septimus Limestone at the southwestern end of Mount Septimus

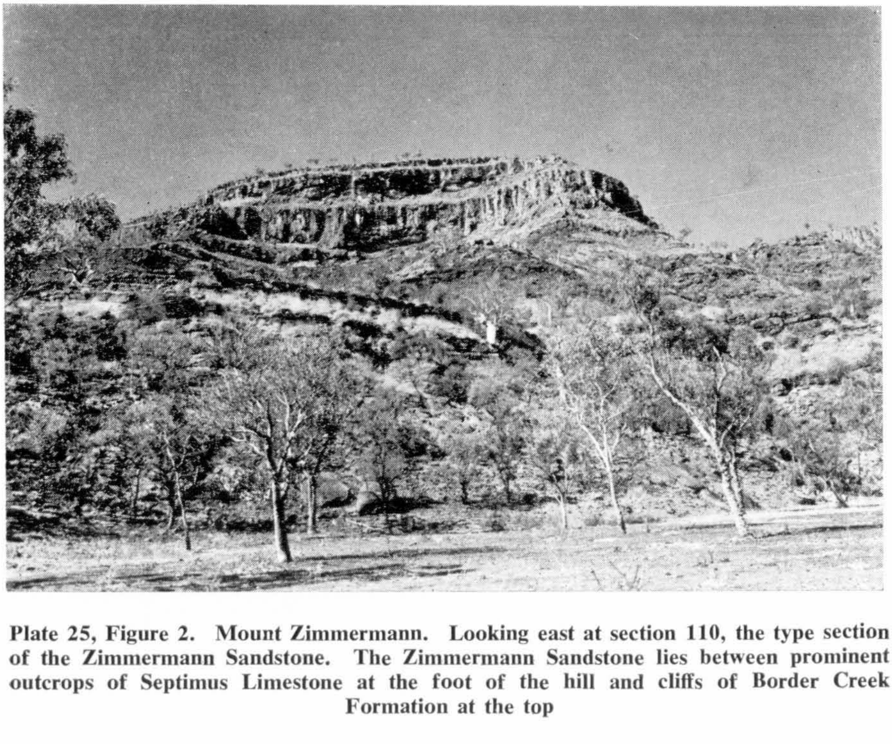


Plate 25, Figure 2. Mount Zimmermann. Looking east at section 110, the type section of the Zimmermann Sandstone. The Zimmermann Sandstone lies between prominent outcrops of Septimus Limestone at the foot of the hill and cliffs of Border Creek Formation at the top

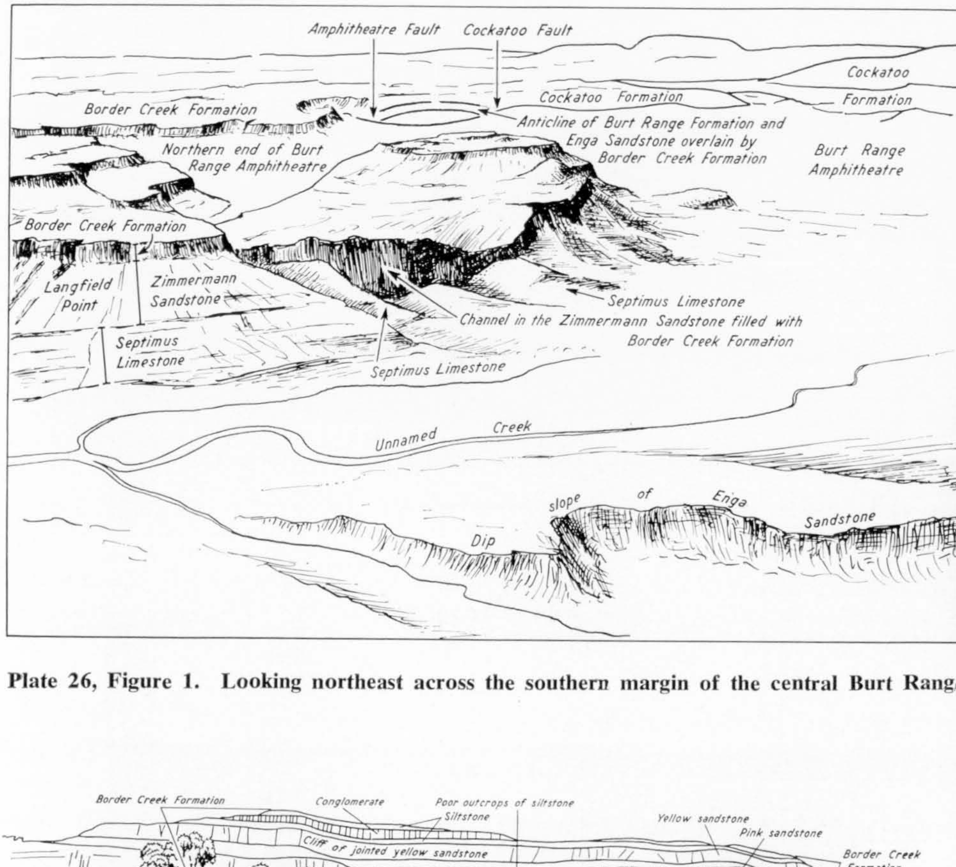


Plate 26, Figure 1. Looking northeast across the southern margin of the central Burt Range

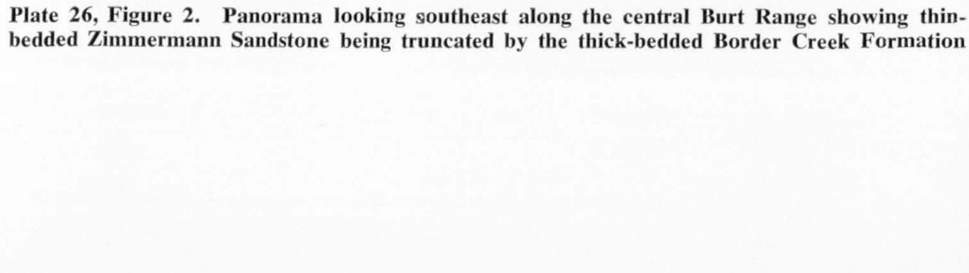


Plate 26, Figure 2. Panorama looking southeast along the central Burt Range showing thin-bedded Zimmermann Sandstone being truncated by the thick-bedded Border Creek Formation

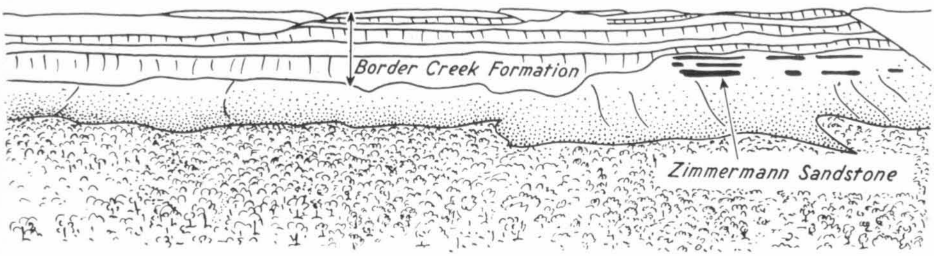


Plate 27, Figure 1. Aerial panorama of the western scarp of the central Burt Range, showing the thin-bedded Zimmermann Sandstone truncated by the thick-bedded Border Creek Formation

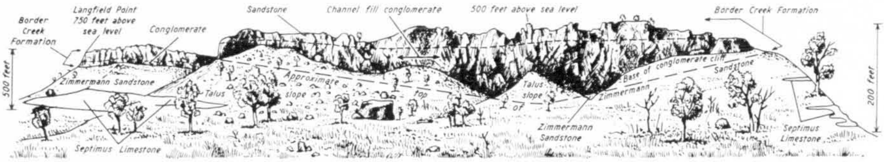


Plate 27, Figure 2. Looking north at the channel fill at the southern margin of the central Burt Range

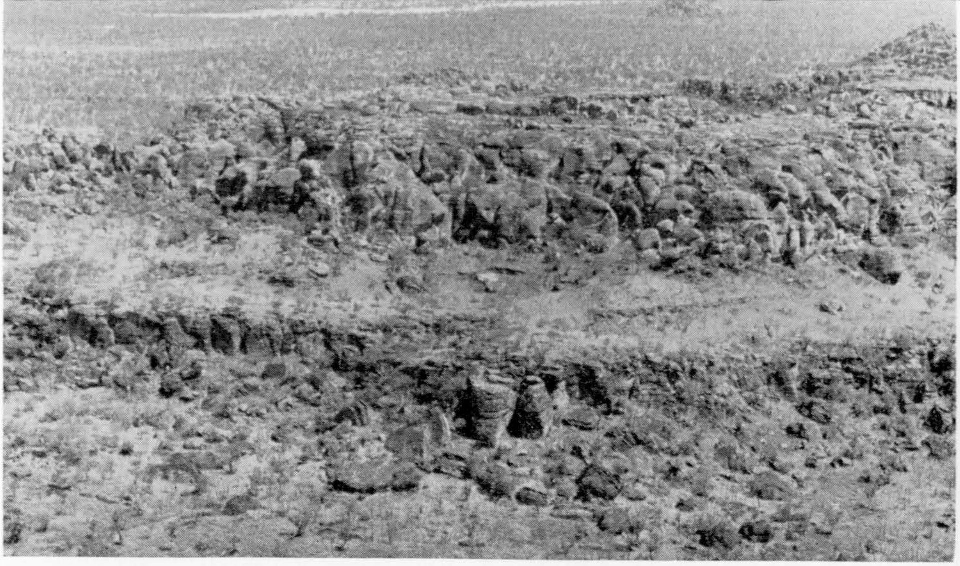


Plate 28, Figure 1. Aerial view looking northwest of the western part of Spirit Hill, showing the turreted cliffs of Border Creek Formation. The Pincombe Range is in the background

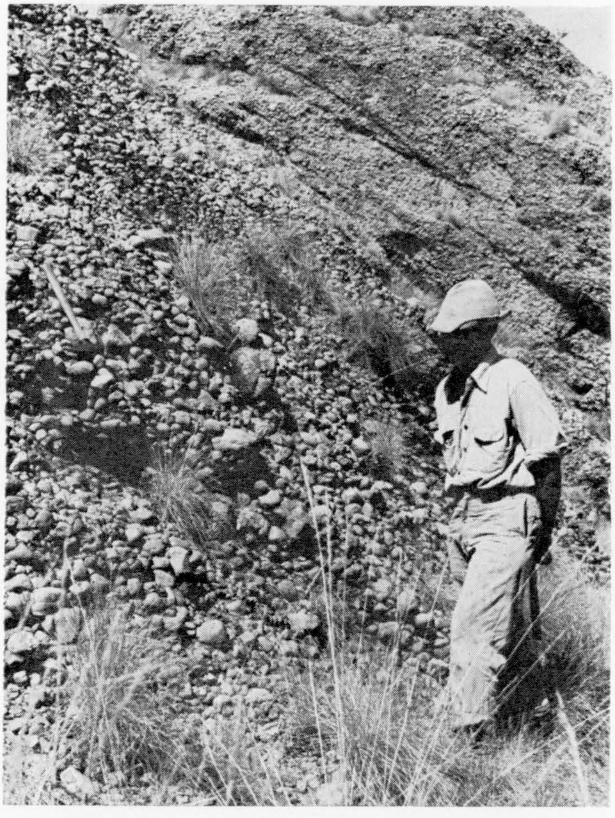


Plate 28, Figure 2. Conglomerate of the Border Creek Formation within the channel in the Zimmermann Sandstone at the southern margin of the central Burt Range

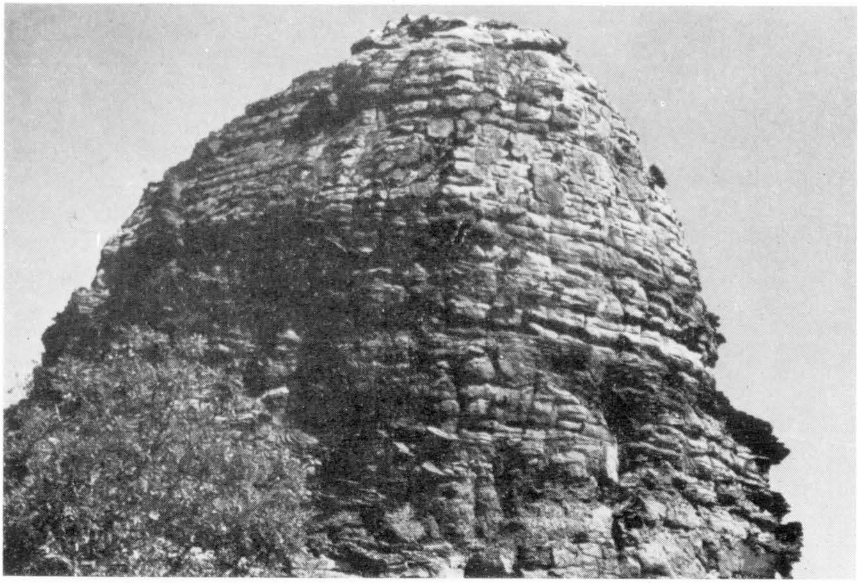


Plate 29, Figure 1. Cone-shaped turret of Border Creek Formation at Milligans Hills, showing the bedding and jointing characteristic of the coarser-grained Palaeozoic quartz sandstone of the Bonaparte Gulf Basin. cf. the Cockatoo Formation of Plate 7, Figure 2

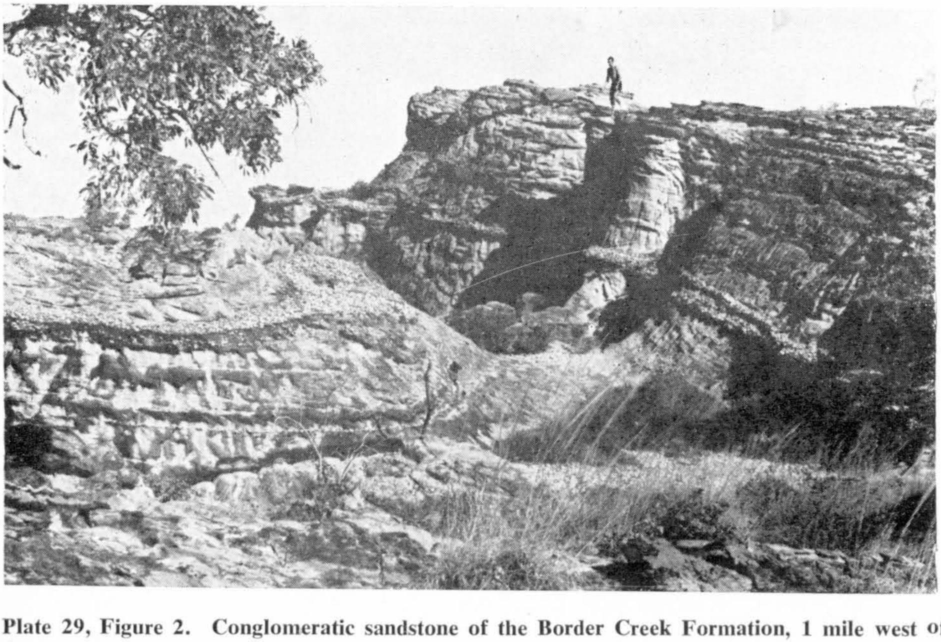


Plate 29, Figure 2. Conglomeratic sandstone of the Border Creek Formation, 1 mile west of Alpha Hill. The outcrop has the pattern of bedding and jointing characteristic of most of the coarse-grained Palaeozoic quartz sandstones of the Bonaparte Gulf Basin. cf. Plate 7, Figure 2

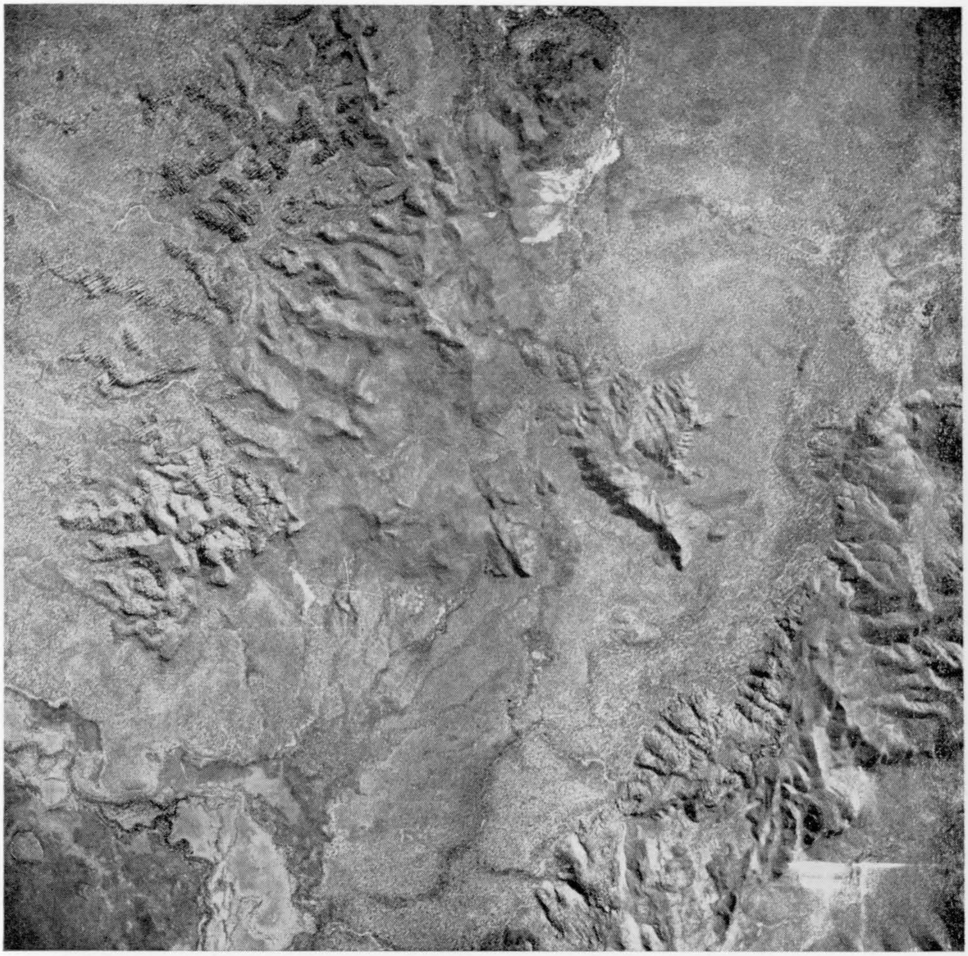


Plate 30. Vertical air-photograph of Spirit Hill showing outcrops of the jointed Border Creek Formation in the west, the Milligans Beds in the middle, and the Burt Range Formation in the southeast. East of Spirit Hill the Cockatoo Formation is separated by the Cockatoo Fault from Precambrian rocks, except at one locality where the Cockatoo Formation overlaps the fault to rest directly on the Precambrian (Plate 7, Figure 2). The geology of the area is given in Figure 53

grey skeletal crinoidal calcisiltite characterizes the interval from 150 to 400 feet. From 400 to 700 feet there is olive-grey crinoidal calcarenite containing abundant brachiopods. The rocks become sandier between 700 feet and the top of the section at 950 feet and are mainly olive-grey or olive-brown sandy skeletal calcarenite, which also contains brachiopods.

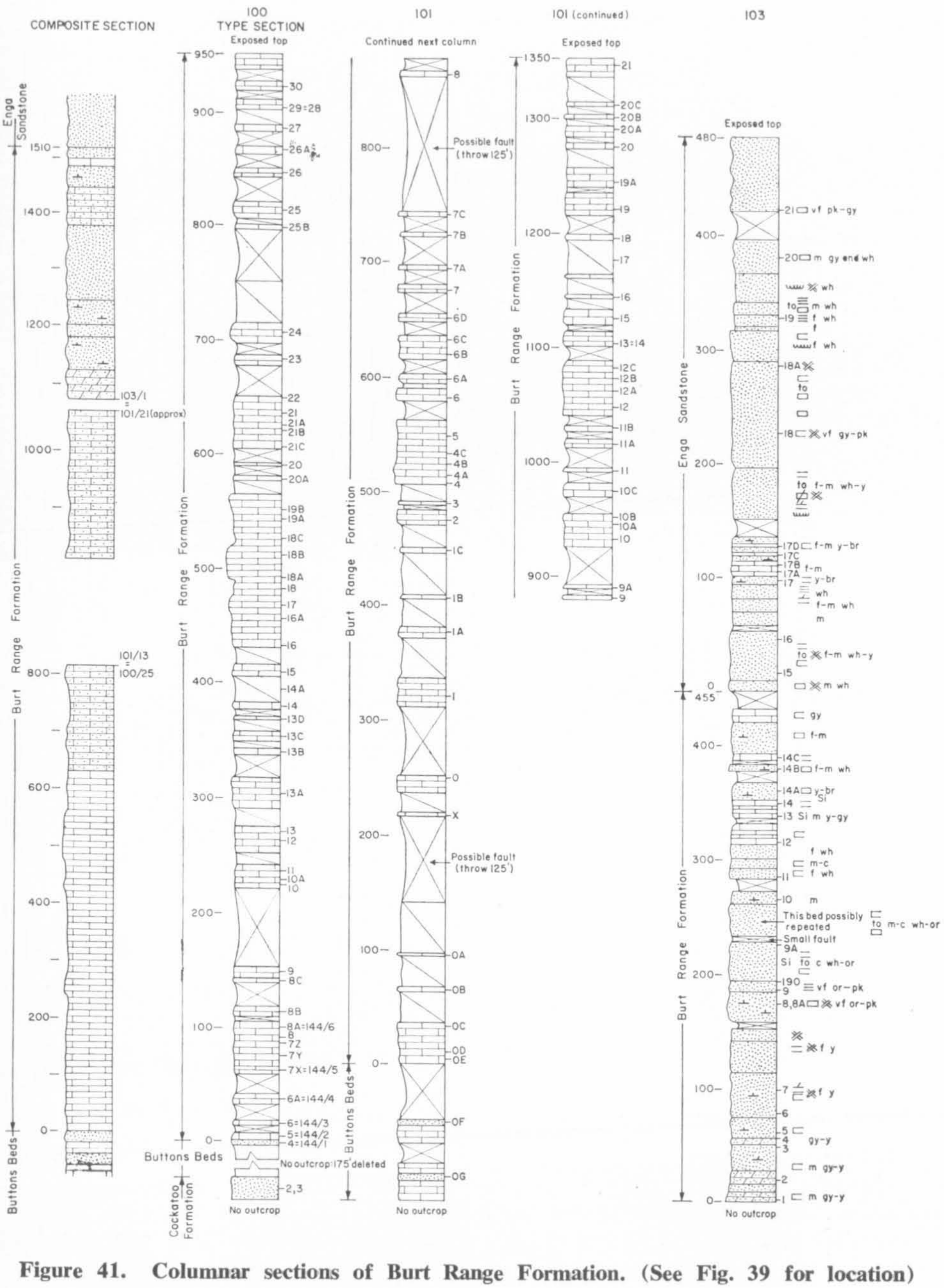


Figure 41. Columnar sections of Burt Range Formation. (See Fig. 39 for location)

Other Sections. The stratigraphic relationships between all the sections measured through the Burt Range Formation are shown in Figure 43. Section 101 extends 250 feet stratigraphically higher than the type section and is used to describe the middle part of the formation. In this description, the middle part of the formation is taken from locality 100/25, or its equivalent locality 101/13, to the top of the 101 section at locality 101/21; i.e. roughly between 800 and 1,100 feet above the base of the composite section.

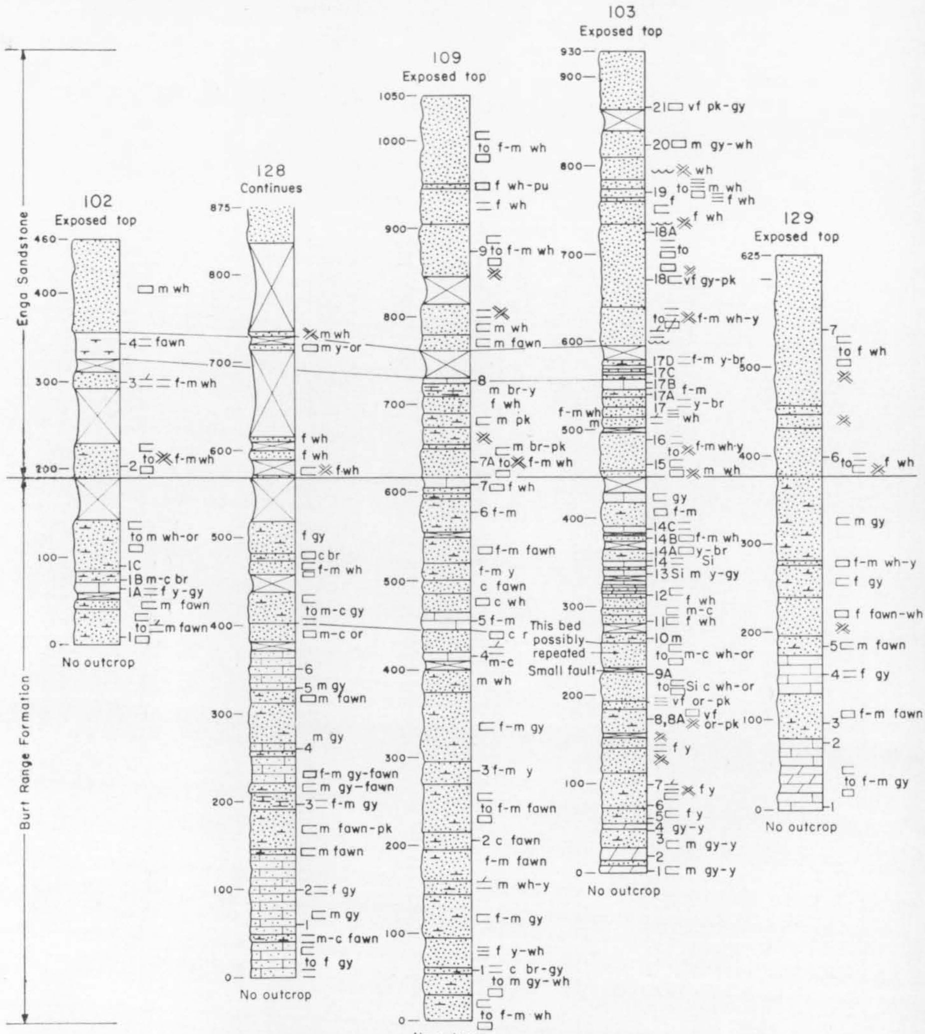


Figure 42. Columnar sections of Burt Range Formation and Enga Sandstone across Enga Ridge. (See Fig. 39 for location)

Most of the lower part of the formation in section 101 is poorly exposed. However, prominent ribs crop out between 500 and 700 feet above the base of the section, and at locality 101/3 concentrations of tabulate coral are preserved in their living position together with abundant gastropods and brachiopods.

The middle part of the Burt Range Formation consists of alternating hard and soft beds of yellow-brown to olive-grey sandy calcarenite. Those in section 101 are more sandy and more thickly bedded than the equivalent calcarenites in the top of the type section, which suggests that at least the middle part of the formation is more sandy in the south. At locality 101/12 a bedding plane contains a mass of straight nautiloids with their apexes oriented between 10° and 15°, indicating a current flowing from that direction (Pl. 21, fig. 2). The sandy calcarenite at locality 101/12 is cross-bedded and also contains lenses of broken brachiopods. The rocks towards the top of the section are poorly exposed, but are lithologically close to those at the base of section 103.

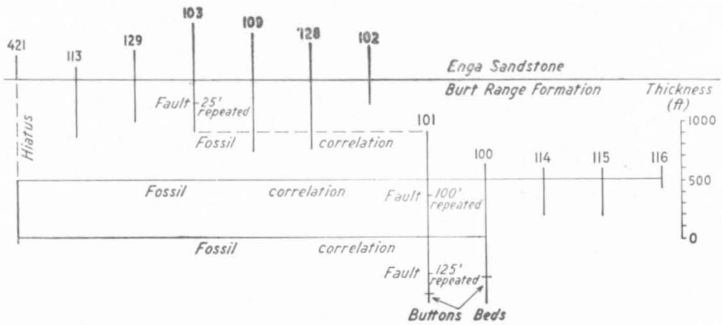


Figure 43. Stratigraphic relationships between sections of Buttons Beds, Burt Range Formation, and Enga Sandstone

The upper part of the formation, taken from section 103, consists of fine to medium-grained yellow-grey dolomitic quartz sandstone at the base, followed by medium to coarse-grained white to orange friable quartz sandstone, which is overlain by alternating beds of fine to medium-grained brown calcareous sandstone and grey-brown sandy limestone. The upper part of the formation grades into the overlying Enga Sandstone, and the boundary is taken at the base of a prominent bench of quartz sandstone containing long vertical worm tubes.

Four other stratigraphic sections have been measured through the upper part of the Burt Range Formation from where it is well exposed along the length of Enga Ridge (Fig. 42). The additional sections were measured to determine if there is any lateral variation in the upper part of the formation, and to obtain additional fossils for stratigraphic control.

Correlations between the sections along Enga Ridge are shown in Figures 42 and 43. With the exception of that between localities 102/4, 109/8, and 103/17, all the correlations are based on lithological evidence. In Figure 42 the lowermost correlation line between sections 128, 109, and 103 is drawn at the top of a medium to coarse-grained orange to white quartz sandstone which is characterized by a rounded castellated outcrop. The line at the base of the Enga Sandstone is drawn at the base of a thick pipe-rock sandstone which forms a prominent bench along the length of the ridge. The topmost line is drawn at the base of a high cliff which caps most of the higher parts of the ridge. Palaeontological evidence from brachiopods, ostracods, and conodonts shows that the beds at localities 102/4, 109/8, and 103/17 are of the same age. Further correlation lines will probably be available when the study of the fossils has been completed.

The columnar sections show that the rocks have little lateral variation and that the main rock types in the reference section (103) extend along the length of Enga Ridge.

Fauna

The fauna of the Burt Range Formation is dominated by brachiopods, conodonts, and ostracods, all of which are useful for correlation within the basin. Brachiopods and conodonts have also proved valuable for correlations with overseas sequences. Conodonts were found in most of the limestone and calcareous sandstone throughout the formation; brachiopods occur abundantly above the 300-foot level; and ostracods were most commonly found in the middle part of the formation.

In places, crinoid columnals constitute up to 90 percent of the rock. Other organisms present in smaller numbers include gastropods, nautiloids, corals, trilobites, polyzoans, scolecodonts, and pelecypods in the more sandy upper part of the formation. In the upper part of the formation there are trace fossils and wood fragments. Algae are scattered throughout the limy beds, and a stromatolitic layer occurs 150 feet above the base of the formation.

Age

The Burt Range Formation was originally dated as Upper Devonian by Matheson & Teichert (1948) by correlation of the lower part of the formation with the '*Productella* limestone' in the Fitzroy Basin. Öpik (*in* Traves, 1955) agreed with the Upper Devonian age and thought that the top of the formation coincided with the end of the Devonian Period. Thomas (1962) recognized that the higher beds were possibly Lower Carboniferous.

The entire formation is now dated as Lower Carboniferous (lower to middle Tournaisian). Jones & Druce (1966), by work on conodonts, correlated the Burt Range Formation with the CUI-CuII$_{\alpha}$ Zones of Germany. From later work Druce (1968) correlated the formation with most of the K Zone of the Avon Gorge section in Britain. Brachiopods support the lower Tournaisian age for the base of the formation. The brachiopod fauna from the basal beds of the overlying Enga Sandstone is correlated with one in the Pierson Formation in Missouri and thence with the CuII$_{\alpha}$ Zone of Germany.

Burt Range Amphitheatre

In the central Burt Range area, the Burt Range Formation crops out at the northern and southern ends of the Burt Range Amphitheatre. The amphitheatre consists of a flat tree-covered plain almost entirely surrounded by hills—the central Burt Range to the west and northwest, the Enga Ridge to the south and southwest, and an unnamed range of Cockatoo Formation to the east (Fig. 44; Pls 22, 23). Access to the amphitheatre is by a valley running between Enga Ridge and central Burt Range or by a narrow water-gap in the eastern wall.

The Burt Range Formation is contained within a fault block bounded by the Amphitheatre and Cockatoo Faults (Figs 39 & 44): the movements on the faults have stepped the rocks up towards the east so that successively older formations are exposed in that direction. The outcrops at either end of the amphitheatre are well layered on the air-photographs (Pls 22, 23) and are exposed as rocky benches on the scarps.

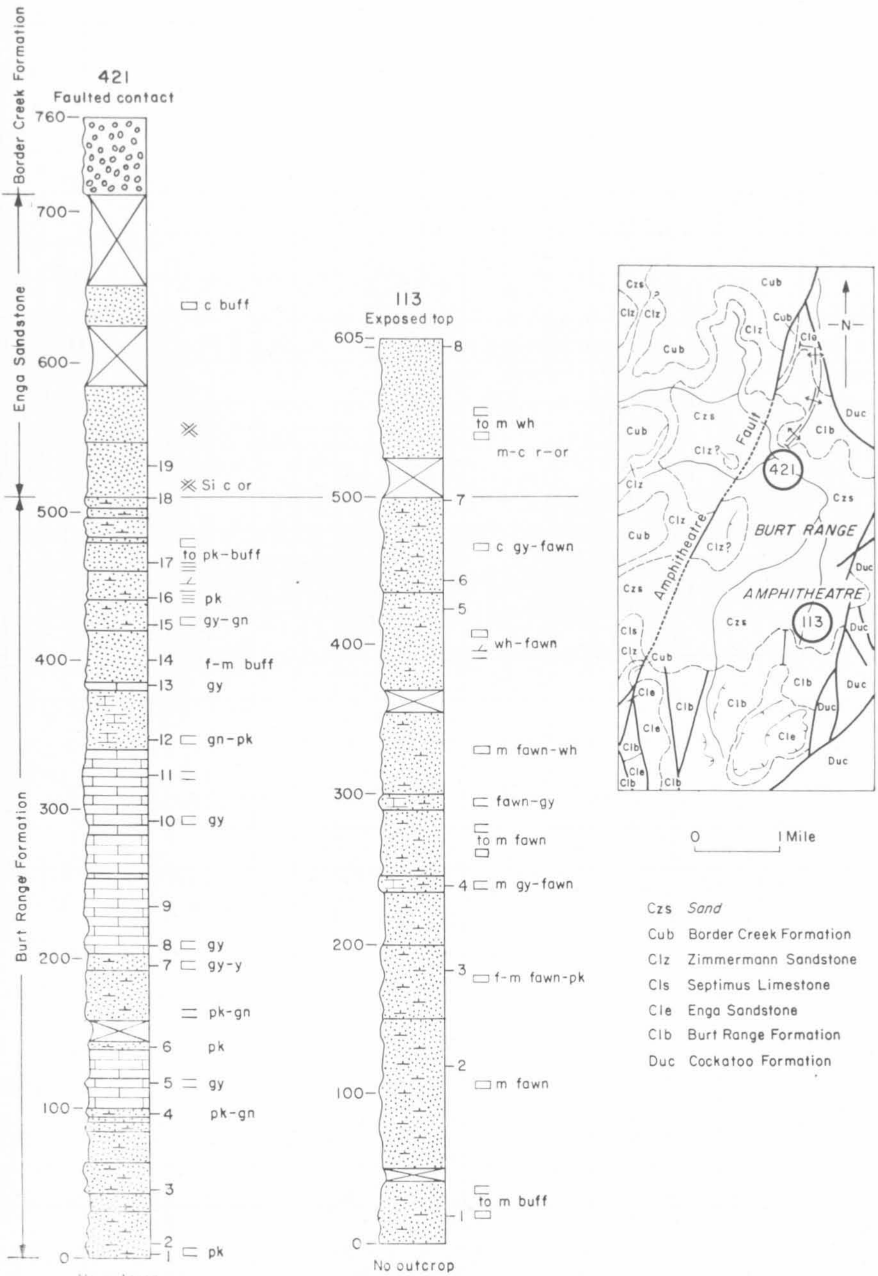


Figure 44. Geological map and columnar sections, Burt Range Amphitheatre. (Modified from photogeological map by R. Richard)

The northern section (421) was measured along the axis of a small anticline in the 'keystone' between the junction of two faults (Figs 39 & 44). The anticline, which was first mapped by Traves (1955), appears to have been formed by lateral or drag movements along the faults. The eastern block of Cockatoo Formation has moved in relation to the Burt Range Formation and Enga Sandstone in the central block, and hence the vertical movement on the faults could not have been responsible for the east-dipping flank of the anticline.

The rocks in section 421 comprise pinkish and grey-green calcareous sandstone in thin to moderately thick beds, with some interbedded sandy limestone cropping out from 0 to 200 feet; medium-bedded grey sandy limestone from 200 to 380 feet; and laminated, locally cross-bedded, buff calcareous sandstone from 380 to 510 feet. Brachiopods show that the section is approximately equivalent to the lower to middle part of the Burt Range Formation, probably to the interval between 350 and 900 feet in the type section; locality 421/5 at 120 feet has the same fauna as the interval 350 to 450 feet in the type section; and locality 421/17 at 465 feet has a fauna similar to that between 800 and 900 feet in the type section.

The overlying buff to orange quartz sandstone contains trace fossils and poorly preserved pelecypods, and is identified as Enga Sandstone. The similar sandstone outcrops which overlie the upper part of the Burt Range Formation, at the southern margin of the amphitheatre, are almost certainly a continuation of the outcrops of Enga Sandstone along Enga Ridge (Fig. 39; Pl. 23). Hence, it appears that there is an unconformity between the Burt Range Formation and Enga Sandstone in the northern part of the amphitheatre, and that in section 421 the upper part of the Burt Range Formation, which amounts to about 500 feet of section, was either eroded or never deposited.

The sediments in section 421 are much more sandy and better exposed, and form higher outcrops than those in the equivalent part of the type section. They are dolomitized in places, especially near the faults, and this, along with the protective cap of Enga Sandstone, may have made them more resistant to erosion than the beds in the type section.

Section 113 was measured at the southern margin of the amphitheatre (Figs 39 & 44). The 500 feet of Burt Range Formation exposed in this section mainly comprises medium to thick-bedded medium-grained fawn to grey calcareous sandstone, with some coarser beds; occasional beds of limestone are interbedded in the middle part of the section. The fossils collected at localities 113/5 and 113/7, from near the top of the formation, indicate horizons in the upper part of the Burt Range Formation. They cannot be precisely correlated with the reference area, but it appears that there is less calcarenite in the upper part of the formation in the amphitheatre area.

The calcareous sandstone is overlain by fossiliferous red to white quartz sandstone identified as Enga Sandstone. The fossils on either side of the boundary indicate that the sequence is probably continuous. If there is a stratigraphic break between the Burt Range Formation and Enga Sandstone in section 113, it is certainly much smaller than the one recognized in section 421 at the northern end of the amphitheatre.

Sorby Hills

At locality 126/5 in the Sorby Hills a sliver of Burt Range Formation has been downfaulted into Upper Devonian Buttons Beds (Fig. 37). The downfaulted beds consist of altered fine-grained quartz sandstone which contains well preserved brachiopods and pelecypods. The brachiopods are the same age as those between 800 and 900 feet above the base of the formation and are dated as middle Tournaisian.

There is no visible contact between the fault sliver and the nearby Precambrian, which elsewhere in the Sorby Hills is overlain by the Upper Devonian Buttons Beds. The sandy nature of the Burt Range Formation suggests that it may have also lapped on to the Pincombe Inlier, but it could equally well have extended as a sheet over the inlier.

Sandy Creek/Legune Area

Scattered outcrops assigned to the Burt Range Formation occur in a narrow belt stretching from Sandy Creek to Flapper Hill, near Legune station (Fig. 45; Map 1). The rocks crop out in low resistant hills, which are commonly capped with banded porcellanite. Many of the outcrops, such as those at Flapper Hill, are completely silicified; others are strongly ferruginized and usually deeply weathered. Because of the alteration, no distinct outcrop pattern is visible on the air-photographs and the exposures appear as low rounded hills rising out of a flat timbered plain.

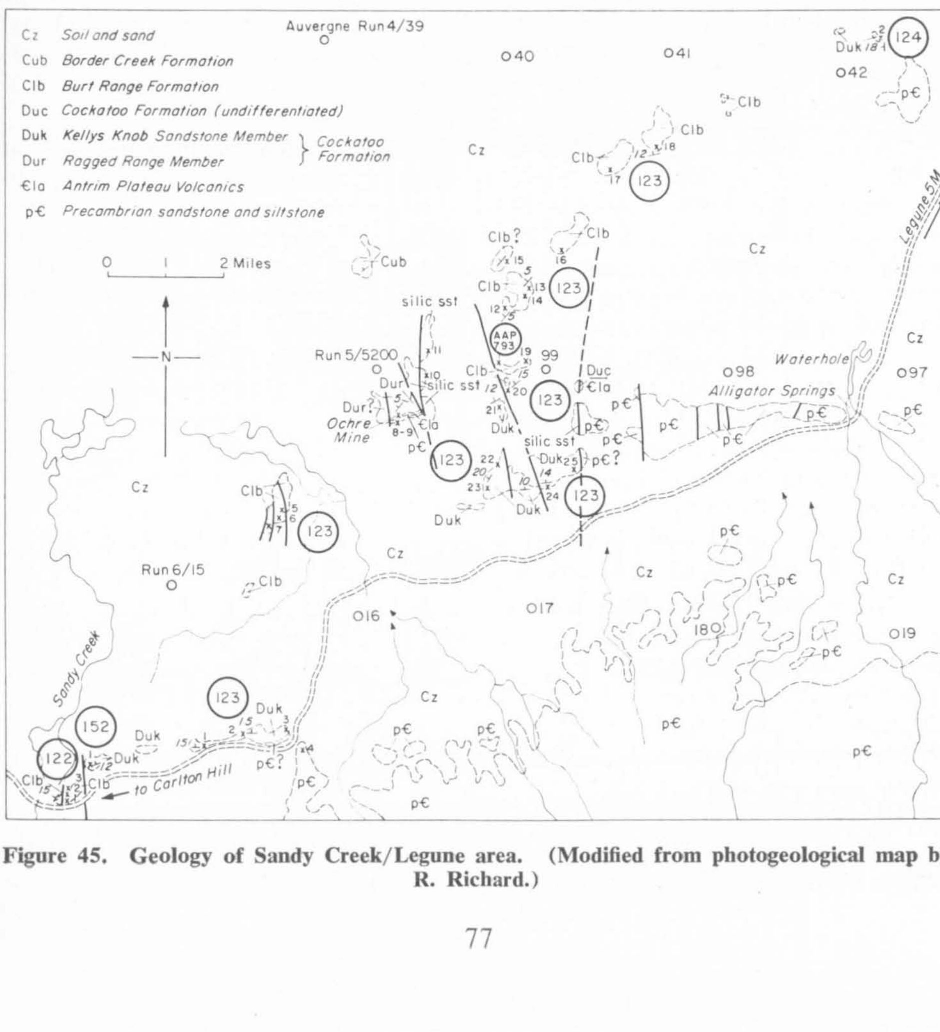


Figure 45. Geology of Sandy Creek/Legune area. (Modified from photogeological map by R. Richard.)

The rocks at Sandy Creek crossing have been examined by a number of geologists. Noakes et al. (1962) named them Sandy Creek Limestone, and on the basis of fossils tentatively correlated them with the Flapper Hill Sandstone. Traves (1955) mapped the outcrops at Sandy Creek as Spirit Hill Limestone, then considered to be part of the Permian Weaber Group. Thomas (App. D. *in* Traves, 1955; 1962), however, considered the brachiopods from Sandy Creek to be most closely allied to Lower Carboniferous species.

The rocks at Sandy Creek comprise well bedded medium-grained fawn to greyish pink dolomite and silicified limestone containing silicified fossils. Overlying the dolomite is a poorly bedded yellow-brown medium-grained fossiliferous sandstone which has been silicified and ferruginized. Near the eastern bank of Sandy Creek, the silicified sandstone is faulted against the underlying dolomite and limestone. The majority of the brachiopods from both rock types suggest a correlation with the middle part of the Burt Range Formation.

Beds of the Burt Range Formation also crop out in a group of low hills, 5 miles northeast of the Sandy Creek exposures (Fig. 45, locs 123/5, 6, & 7). They are faulted and many have been silicified and ferruginized. At locality 123/5 silicified quartz sandstone and thinly bedded fine-grained white and purple quartz sandstone containing indeterminate plant remains are exposed. The beds appear to be underlain by fine to medium-grained fawn calcareous sandstone (loc. 123/6), which is generally medium-bedded and in places cross-bedded. A fault downthrown to the east separates the calcareous sandstone from beds of similar lithology at locality 123/7.

A row of hills mapped as Burt Range Formation extends from a point about 2 miles east of the Ochre mine northeast towards Legune station (Fig. 45). In the southernmost hill, at locality 123/20, flaggy outcrops of white to purple laminated siltstone and fine to medium-grained quartz sandstone containing crinoid ossicles are overlain by a coarse to medium-grained fossiliferous reddish feldspathic sandstone. A brachiopod from the topmost sandstone suggests that the beds belong to the upper part of the Burt Range Formation.

A quarter of a mile to the north, in the hills around localities 123/19 and AAP793 (Fig. 45), interbedded yellow to white flaggy siltstone, containing trace fossils, and interbedded sandstones are overlain by a coarse to medium-grained red fossiliferous sandstone (AAP793). The hills are capped with banded purple and white porcellanite which is lithologically similar to the Lower Cretaceous sediments capping hills in the northeastern part of the basin near Port Keats. Brachiopods collected from locality AAP793 suggest a correlation with the upper part of the Burt Range Formation or even the basal beds of the Enga Sandstone.

In the hills 1 mile farther north (Fig. 45, locs 123/12, 13, & 14) a similar sequence of siltstone with trace fossils and sandstone with brachiopods overlies grey to brown silicified calcareous sandstone and limestone. The brachiopod fauna at locality 123/4, preserved in yellow-brown medium to coarse-grained feldspathic sandstone, is similar to that from the upper part of the Burt Range Formation. The outcrops at locality 123/15, doubtfully referred to the Burt Range Formation, consist of barren coarse-grained greyish white quartz sandstone; some of the sandstone is cross-bedded.

Three prominent hills to the northeast (Fig. 45, locs 123/16, 17, & 18) consist of rubbly outcrops of friable red, yellow, or white medium to coarse-grained quartz sandstone. In the hill at locality 123/16 about 100 feet of sandstone is overlain by 40 feet of banded purple and white siltstone or porcellanite. The fossils from locality 123/16 are the same as those in the upper part of the Burt Range Formation in the type area, and a brachiopod from locality 123/17 is most closely comparable with one from the base of the Enga Sandstone. The sandstone in the northernmost hill (loc. 123/18) overlies about 25 feet of medium-bedded grey to fawn crinoidal calcarenite.

Noakes et al. (1952) introduced the name Flapper Hill Sandstone for the outcrops at Flapper Hill, 4 miles northwest of Legune station. They were uncertain of the stratigraphic relationships of the unit, but suggested that it could be older than the Point Spring Sandstone, and may interfinger with the rocks at Sandy Creek. Traves (1955) also used the name Flapper Hill Sandstone and suggested that it may be represented by sandstones above or below the limestone at Spirit Hill. Thomas (1962) listed fossils collected from Flapper Hill and concluded that they were Lower Carboniferous (Dinantian).

The rocks at Flapper Hill consist of silicified and ferruginized medium-grained light grey to red quartz sandstone. Most of the hill is covered by talus of rounded sandstone boulders, but some of the beds at the top of the hill appear to be in situ. Glover et al. (1955, unpubl.) reported a lenticular outcrop of grey limestone, which we did not see, midway up the hill. Brachiopods from Flapper Hill suggest a correlation with the upper part of the Burt Range Formation.

Enga Sandstone

The Enga Sandstone crops out in the southeastern part of the Bonaparte Gulf Basin on the top of the western scarp and eastern dipslope of Enga Ridge (Fig. 39). Other outcrops occur in the Burt Range Amphitheatre area and in hills 4 miles northeast of Mount Septimus.

Matheson & Teichert (1948) included the sandstone capping Enga Ridge in the Burt Range Series. Noakes et al. (1952) gave the sandstone the name of Snowie Sandstone, but this became invalid after the Lands and Survey Department of Western Australia replaced the proposed name Snowie Ridge by Enga Ridge. Traves (1955) called the formation Enga Sandstone.

The outcrops along Enga Ridge are regularly layered. The formation is always well exposed in the scarp on the western side of the ridge and in the castellated pinnacles on the deeply dissected eastern slope. Eucalyptus trees, low shrubs, and spinifex grow on the Enga Sandstone.

On the southeastern margin of the basin the Enga Sandstone is cut off by the Cockatoo Fault. Immediately north of Enga Ridge it disappears beneath sand cover.

Stratigraphic sections measured through the Enga Sandstone include six along Enga Ridge (Fig. 42), three in the Burt Range Amphitheatre area (Figs 39 & 42), and one in the low hills 4 miles northeast of Mount Septimus (Fig. 46).

Type Section. The upper part of section 103 (Fig. 42) measured near the middle of Enga Ridge is here designated as the type section. The lower boundary, with the Burt Range Formation, is 445 feet stratigraphically above the base of the section at latitude 15°49′S., longitude 128°56′E.

The Enga Sandstone is a clean quartz sandstone with minor calcarenite beds near the base. The sandstone is a well sorted fine to medium-grained white quartz sandstone with moderately to well rounded sand grains. At the surface it is porous and appears to be weakly cemented by a little clay. The sandstone weathers to orange-red.

Near the base of the formation there is a thin to medium-bedded white to yellow quartz sandstone containing long vertical tubes (Pl. 24, fig. 1), pelecypods, and brachiopods. About 100 feet above the base of the formation there is 50 feet of fossiliferous calcarenite and interbedded calcareous sandstone. They are succeeded by fine to medium-grained white quartz sandstone, which is moderately to thickly bedded and crops out in numerous benches or steep cliffs. Some beds are cross-stratified and others contain ripple marks. The ripple marks 660 feet above the base of section 103 are generally symmetrical, but some indicate a current flowing from 105°. At 740 feet, asymmetrical ripples were formed by a current flowing from 330°. Trace fossils, including *Rhizocorallium,* are present in many beds, but shelly marine fossils are less common than in the lower parts of the formation. The sandstone between 795 and 825 feet above the base of section 103 has bands of black ferruginous cement. The stratigraphically highest beds in the section are very fine-grained white quartz sandstone.

The contact with the underlying Burt Range Formation has been described on page 73.

The topmost beds in the type section run eastwards beneath sand cover and their contact with the overlying Septimus Limestone is obscured. The only known contact, at locality 111 near the Amphitheatre Fault (Fig. 39), is probably paraconformable (see below). The calcareous sandstone overlying the beds of typical Enga Sandstone in section 111 have been placed in the Septimus Limestone because of the similarity in lithology. Glover et al. (1955, unpubl.) referred the calcareous sandstone to the upper part of the Enga Sandstone.

A total of 485 feet of Enga Sandstone is exposed in the type section. Taking into account 35 feet of additional section in section 111, the thickness of the formation is estimated at 520 feet.

Other Sections. The other sections measured across Enga Ridge (Fig. 42, sections 102, 128, 109, & 129) show only minor differences compared with the type section.

The marl exposed beneath the high cliff-forming sandstone in section 102, at the northern end of Enga Ridge, is laterally equivalent to the calcarenite and calcareous sandstone at the same stratigraphic level in the type section and in section 109. These calcareous beds are represented by sandstone in section 129 at the southern end of Enga Ridge.

Beds identified as Enga Sandstone overlie the Burt Range Formation in the Burt Range Amphitheatre (Figs 39 & 44, sections 421 & 113); their relationship with the underlying formation has been discussed on page 76. In section 421, at the northern end of the amphitheatre, 140 feet of medium to coarse-grained well sorted buff to orange quartz sandstone unconformably overlies carbonate rocks of the Burt Range Formation. The sandstone is silicified at the contact with the underlying formation, and contains poorly preserved pelecypods and trace fossils. Glover et al. (1955, unpubl.) reported lepidodendroid plant fragments from a locality near the line of section 421.

At the southern end of the amphitheatre, about 100 feet of medium to coarse-grained well sorted white quartz sandstone containing pelecypods and trace fossils overlies, probably conformably, calcareous sandstone of the Burt Range Formation. The sandstones in sections 113 and 421 are coarser than those in the type section, and were presumably deposited closer to the margin of the basin.

Steeply dipping quartz sandstone, 380 feet thick, is exposed in a low hill (Fig. 39, loc. 78) near the Cockatoo Fault, 4 miles northeast of Mount Septimus. The sandstone is mainly a thin to medium-bedded white to yellow fine to medium-grained quartz sandstone, but pebbles are present in coarse-grained sandstone near the base of section 78 (Fig. 46). Many of the lower beds contain trace fossils; pelecypods, brachiopods, and lepidodendroid plant fossils have been found at localities 78/1, 2, and 3, and a shark, ?*Ctenacanthus* (Joyce G. Tomlinson, BMR, pers. comm.), and an indeterminate goniatite and *Leptophloeum australe* (M'Coy) from locality AAP28. Above 190 feet, the beds are commonly cross-bedded and contain pipe-rock beds, some of which are silicified. The sandstone in section 78 appears to overlie silicified limestone (possibly Burt Range Formation) near a fault zone on the eastern side of the hill (Fig. 39). The sandstone on the eastern side of the fault contains boulders up to 6 inches in diameter, not seen in section 78, and loose blocks of sandstone contain large logs up to 26 inches long by 18 inches wide of *Leptophloeum australe* and lepidodendroid plants and rhynchonelloid brachiopods. These beds are tentatively identified as Enga Sandstone.

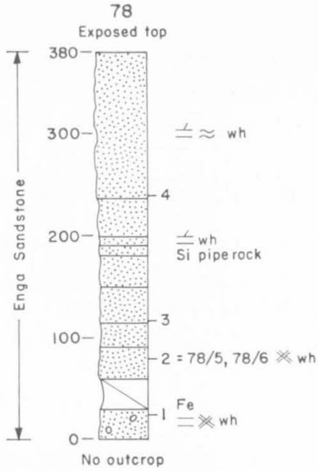


Figure 46. Columnar section of Enga Sandstone 3 miles northeast of Mount Septimus

The identification of the Enga Sandstone in Spirit Hill No. 1 (Thomas *in* Hare et al., 1961, unpubl.; Drummond, 1963, unpubl.) is rejected (see p. 102). Thomas doubtfully referred the interval between 2,013 and 2,469 feet to the Enga Sandstone, and Drummond called that between 1,215 and 1,561 feet Enga Sandstone. Figure 54 shows that this formation does not occur in the well. From palaeontological evidence, Thomas' Enga Sandstone(?) must now be regarded as Upper Devonian Buttons Beds(?), and Drummond's Enga Sandstone as Burt Range Formation.

Fauna

Pelecypods and brachiopods have been collected from localities 103/15 and 16 in the lower part of the formation. The marl and calcarenite overlying the lowermost sandstone contain a rich fauna of brachiopods, ostracods, polyzoans, and trilobites. At locality 102/4 the marls have an extremely rich fauna, and many of the brachiopod species from this locality are not present at the same stratigraphic level in the south, probably because they favoured a quieter and deeper environment. Fossils are less common in the upper part of the formation: brachiopods and pelecypods have been collected from locality 103/19; and scattered poorly preserved pelecypods have been found at locality 139/2 near the top of the formation.

Age

Brachiopods from near the base of the formation indicate a correlation with the Pierson Formation of Missouri, USA, which according to Branson (1944) is equivalent to the Chouteau Formation of the Mississippi Valley. Collinson et al. (1962) correlated the Chouteau Formation with part of the $CuII_{\alpha}$ Zone of Germany. Conodonts from near the base of the formation indicate a correlation with the upper part of the K Zone of the Avon Gorge section in Britain (Druce, 1968).

Septimus Limestone

The Septimus Limestone crops out mainly on the lower parts of Mount Septimus and along the western scarp of the central Burt Range (Pl. 22). There are smaller outcrops in the Burt Range Amphitheatre, against the Amphitheatre Fault, on the northern tip of central Burt Range 2 miles east of Mount Septimus (Fig. 39), and in an isolated locality half a mile east of Spirit Hill (Fig. 53). Thomas (1962) recorded another outcrop, 3 miles northeast of Spirit Hill, which we could not find.

The limestones in the central Burt Range were first examined by Matheson and Teichert (1948), and were dated as Carboniferous. Noakes et al. (1952) introduced the name Mount Septimus Limestone, which was changed by Traves (1955) to Septimus Limestone. The palaeontology of the formation was discussed by Thomas (1962, and in press).

The Septimus Limestone crops out in prominent benches on Mount Septimus and along the central Burt Range. It is well exposed in the middle and upper parts of the section, but the lower part is usually covered by sand. On the air-photographs the limestone has an evenly layered pattern (Pl. 22). Low native cotton trees, a few baobab trees, and tall grass grow on the limestone.

Sections (Fig. 47) have been measured at regular intervals across Mount Septimus and the central Burt Range (Fig. 39).

Type Section. Section 104, on the northwestern flank of Mount Septimus, is here chosen as the type section; it comprises 590 feet of thin-bedded yellow-brown and olive-grey sandy calcarenite, with a fawn calcareous sandstone between 420 and 490 feet (Fig. 47). The co-ordinates of the base of the section are latitude 15°43′S., longitude 128°59′E.

The contact with the underlying Enga Sandstone is not exposed. In the lowermost 100 feet there are isolated beds of thin to medium-bedded yellow to brown or orange sandy skeletal calcarenite. Brachiopods are scattered throughout the carbonate rock and there is a polyzoan limestone between 65 and 80 feet. Thomas (1962) placed these fossils in his assemblage 'd'.

In the overlying 200 feet of section there are more massive outcrops of thin-bedded olive-grey sandy skeletal calcarenite; some beds are cross-stratified on a small scale, and contain silicified broken brachiopod shells. Three thin beds of calcareous sandstone crop out immediately beneath the 300-foot level, at the foot of the scarp of Mount Septimus.

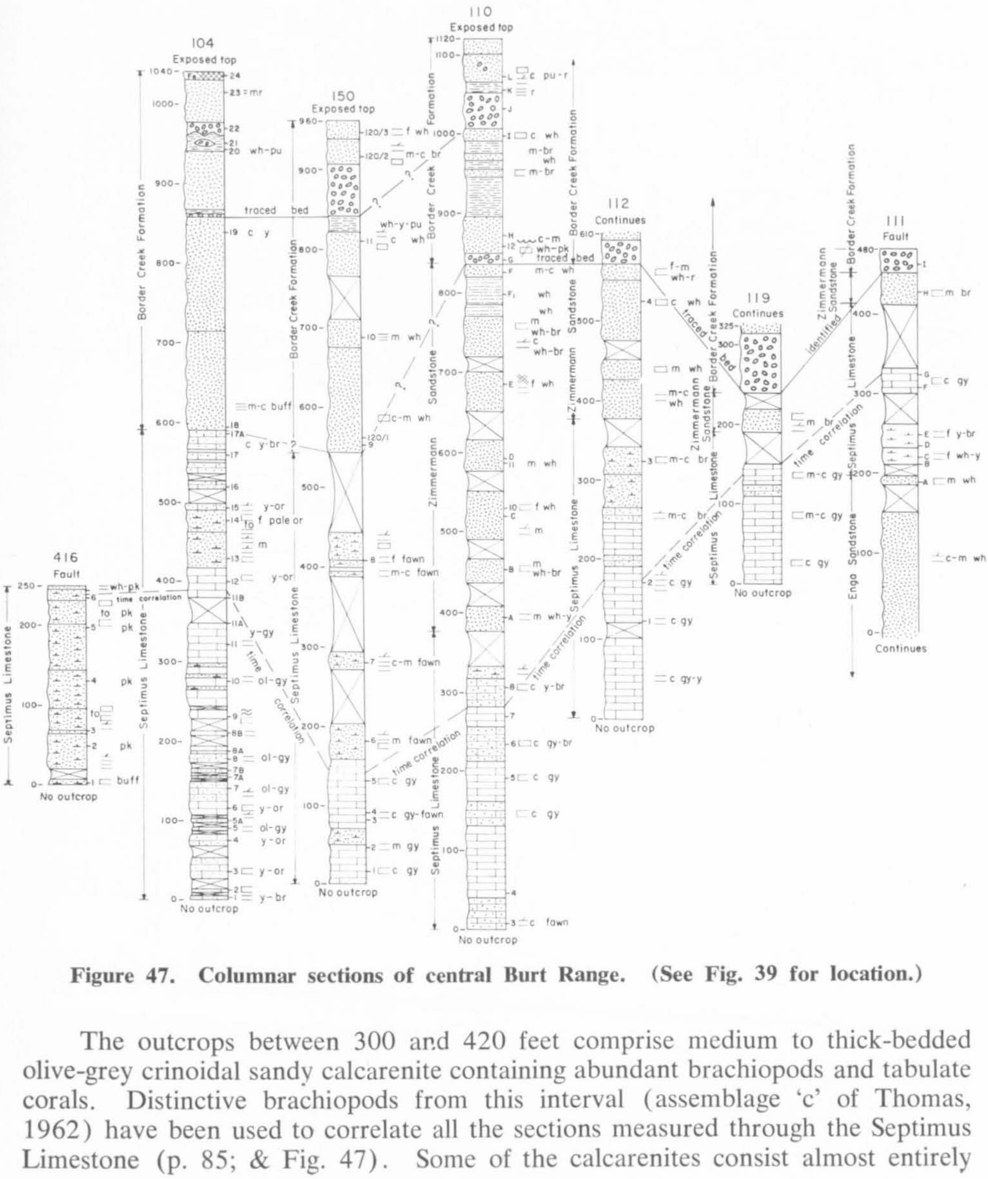


Figure 47. Columnar sections of central Burt Range. (See Fig. 39 for location.)

The outcrops between 300 and 420 feet comprise medium to thick-bedded olive-grey crinoidal sandy calcarenite containing abundant brachiopods and tabulate corals. Distinctive brachiopods from this interval (assemblage 'c' of Thomas, 1962) have been used to correlate all the sections measured through the Septimus Limestone (p. 85; & Fig. 47). Some of the calcarenites consist almost entirely of crinoid columnals. The presence of an intraformational breccia, containing subrounded to subangular clasts of limestone up to 9 inches long and 4 inches high, in the upper part of the unit suggests that there was contemporaneous erosion of some of the Septimus Limestone (Pl. 24, fig. 2).

The lithology changes abruptly between 420 and 490 feet to a brown-weathering medium-bedded pink to fawn medium-grained calcareous and dolomitic quartz sandstone. Many beds are cross-stratified, with sets between 6 and 18 inches thick. Masses of crinoid columnals as well as crinoid calices, an echinoid, brachiopods, and gastropods have been collected from throughout the unit. Thomas (1962) assigned this fauna to his assemblage 'b'.

The remainder of the section to 590 feet is a crinoidal yellow-brown sandy calcarenite containing abundant brachiopods (assemblage 'a' of Thomas, 1962), and masses of tabulate corals up to 3 feet across and 9 inches high which are presumably in situ. The calcarenite is disconformably overlain by cliff-forming barren sandstone of the Border Creek Formation.

In the type area, the contact with the underlying Enga Sandstone is covered by sand and the precise relationship between the Enga Sandstone and the Septimus Limestone is unknown. Fossils show that there is little likelihood of an hiatus between the two formations because conodonts from the base of the Enga Sandstone (no specimens are known from the upper beds) and those from the base of the Septimus Limestone are both typical of the upper part of the K Zone in the Avon Gorge section in Britain (Druce, 1968).

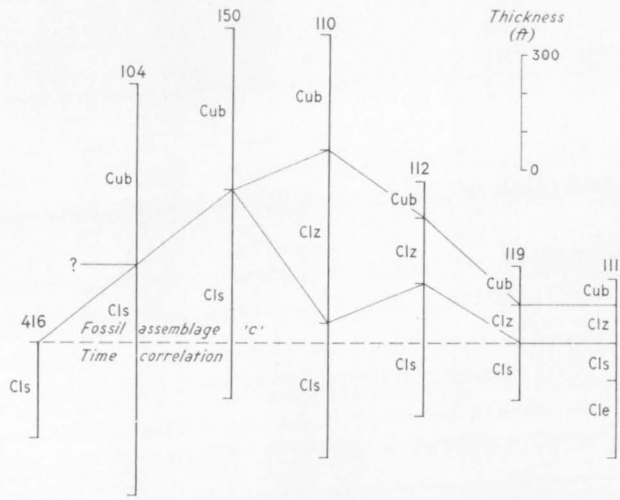


Figure 48. Disconformities in central Burt Range showing eroded upper surfaces of Septimus Limestone and Zimmermann Sandstone

However, an hiatus is thought to exist between the Enga Sandstone and Septimus Limestone at the southern end of the Burt Range Amphitheatre, where a calcarenite containing brachiopods from Thomas' assemblage 'c', together with 50 feet of barren calcareous sandstone, overlies, probably paraconformably, the

Enga Sandstone (Figs 47 and 48). In the type area this hiatus could be represented by some of the lowermost 300 feet of Septimus Limestone (Thomas' assemblage 'd').

Other Sections. In section 150, at the southwestern end of Mount Septimus, the Septimus Limestone (Pl. 25, fig. 1) is also overlain by the Border Creek Formation. A correlation based on brachiopods from Thomas' assemblage 'c' between this and the type section (Figs 47 & 48) shows that the calcareous sandstone towards the top of the formation is thicker in section 150, and that the uppermost beds of calcarenite are absent or not exposed.

The uppermost calcarenite containing Thomas' assemblage 'a' is not known south of Mount Septimus, and the correlation of sections 150, 110, 112, 119, and 111 (Figs 47 & 48) shows that the top of the Septimus Limestone is irregular and that the formation generally thins out towards the south. In the two southernmost sections even the calcareous sandstone is missing and the youngest calcarenite contains brachiopods from Thomas' assemblage 'c'. The irregular upper surface and progressive thinning towards the south suggest that there was an erosional break before the deposition of the overlying formation (Fig. 48). The erosion may have been caused by a gentle uplift associated with faulting south of the Burt Range area.

In the southern central Burt Range the Septimus Limestone is overlain, probably disconformably, by the Zimmerman Sandstone. The sandstone contains brachiopod species, known also from the Septimus Limestone, which may indicate that part of the Zimmermann Sandstone is laterally equivalent to the missing upper part of the Septimus Limestone. All the species so far identified, however, range into the Visean, and have been found in the Bonaparte Beds, Milligans Beds, and Utting Calcarenite; they are not sufficiently diagnostic to indicate whether the two formations are laterally equivalent. Because of the irregular surface on the Septimus Limestone we favour the idea of a disconformity between the two formations. The hiatus was brief and it is not shown in the correlation chart (Fig. 40).

A closely comparable example of erosion is provided by the Zimmermann Sandstone itself, which is deeply channelled by the overlying Border Creek Formation and is much thinner at its southernmost outcrop than in the type section of the western scarp of the central Burt Range (Figs 47 & 48).

An outcrop of sandy carbonate rocks 2 miles east of Mount Septimus, on the northern tip of the central Burt Range (Fig. 39), is identified as Septimus Limestone. The outcrop is bounded by faults on two sides and the Septimus Limestone is faulted against the overlying Border Creek Formation. Near the faults the rocks are strongly jointed and dolomitized. In section 416 (Fig. 47), 245 feet of dolomitic and calcareous sandstone is overlain by 5 feet of white to pink quartz sandstone. The calcareous sandstone is pink, medium to thickly bedded, sometimes cross-bedded, and medium-grained; it contains silicified brachiopods and, in places, masses of tabulate coral which appear to be in situ.

These rocks are much more sandy than their equivalents in the type section, and in the central Burt Range (Fig. 47) they contain fewer shelly fossils, and hence it is likely that they were deposited closer to the shore.

An isolated outcrop of Septimus Limestone at locality 272, half a mile east of Spirit Hill (Fig. 53), is described on page 101.

Fauna

Thomas (1962) recognized four faunal assemblages based mainly on brachiopods in the Septimus Limestone, and gave a comprehensive list of brachiopod, mollusc, trilobite, coral, blastoid, ostracod, and conodont species. He has also described an echinoid (Thomas, 1965a).

Age

Thomas (1962) has suggested that the brachiopods from the Septimus Limestone indicate a late Tournaisian to early Visean age. The brachiopods being described by J. Roberts suggest a slightly older age, and the conodonts show that the Septimus Limestone is equivalent to the uppermost part of the K Zone and lower half of the Z Zone (both Tournaisian) of the Avon Gorge section in Britain (Druce, 1968).

Zimmermann Sandstone (new name)

Zimmermann Sandstone is the name here given to the sandstone between the Septimus Limestone and the Border Creek Formation in the southern part of the central Burt Range. The area of outcrop is only 15 square miles (Fig. 39; Pl. 22). The name is taken from Mount Zimmermann, the highest point in the central Burt Range (Pl. 25, fig. 2).

Traves (1955) mapped the sandstone and conglomerate overlying the Septimus Limestone in the Burt Range area as Weaber Group. We have divided them into the marine Zimmermann Sandstone and the presumably freshwater Border Creek Formation.

The Zimmermann Sandstone crops out in the scarps of the central Burt Range, particularly on the western scarp, and at one locality on the southern edge of the Burt Range Amphitheatre. The formation is topographically subdued and crops out as thin brown bands beneath cliffs of the overlying Border Creek Formation. On the air-photographs the sandstone has a uniform to faintly bedded pattern.

Type Section. Section 110 (Fig. 47) at Mount Zimmermann is here chosen as the type section; it comprises 460 feet of brown to white quartz sandstone, with interbedded white siltstone in the upper part. The co-ordinates of the base of the section are latitude 15°47′S., longitude 128°59′E.

The rock is a friable well sorted thin to medium-bedded medium-grained quartz sandstone with moderately well rounded quartz grains. The grains were probably once cemented by calcite, but the cement has been leached from the outcropping rocks. Some of the sandstones are cross-bedded, and many contain trace fossils, including *Rhizocorallium.* Brachiopods, pelecypods, and polyzoans have been collected at localities 110/10 and 110/11, and poorly preserved brachiopods have been recorded in the interval from 820 to 835 feet above the base of the section (Fig. 47).

Towards the top of the formation thin-bedded white siltstone is interbedded with the sandstone. The siltstone is indistinguishable from that in the overlying Border Creek Formation.

The contact with the underlying Septimus Limestone is not exposed, but the irregular top of the limestone suggests that it is disconformable. The upper surface of the Zimmermann Sandstone is eroded and deeply channelled, and the formation

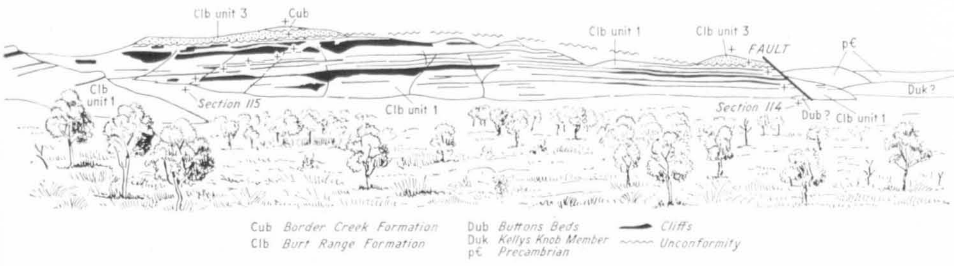


Plate 31, Figure 1. Panorama looking northwest from Spirit Hill cave, showing a disconformity within the Burt Range Formation. The well bedded calcareous sandstone (Unit 1) is overlain at both ends of the hill by quartz sandstone (Unit 3). The southern outcrop of sandstone rests on beds about 180 feet stratigraphically lower in the Burt Range Formation than the northern sandstone outcrop. In the northern part of the hill the Burt Range Formation is disconformably overlain by the Border Creek Formation at the highest point on the horizon

Plate 31, Figure 2. Aerial view looking northeast at the southeastern part of Spirit Hill. In the foreground is bedded quartz sandstone (Buttons Beds?), overlain by thick-bedded calcareous sandstone (Unit 1), succeeded disconformably near the top of the hill by quartz sandstone (Unit 3) of the Burt Range Formation. A minor fault crosses the southern part of the hill

Plate 32, Figure 1. Coarse calcareous sandstone and conglomerate at locality 116-5 in the Milligans Beds? at Spirit Hill. The large subangular clasts are limestone, the rounded pebbles Precambrian quartzite, and the laths Precambrian siltstone. Photo: J. Zawartko

Plate 32, Figure 2. Low oblique air-photograph of well jointed Border Creek Formation, western part of Spirit Hill

Plate 33, Figure 1. Weaber Range. Looking west along the scarp, a few miles east of Point Spring. Base of section 458 at lower right-hand corner. Smooth slope of Burvill Beds overlain by cliffs of Point Spring Sandstone

Plate 33, Figure 2. Vertical air-photograph of Point Spring Sandstone in scarp of Weaber Range ½ mile west of base of section 458. The deeply etched cross-bedded quartz sandstone is crossed by three sets of joints, and is overlain by flat-bedded sandstone, without joints. The field of view is about ⅜ mile across

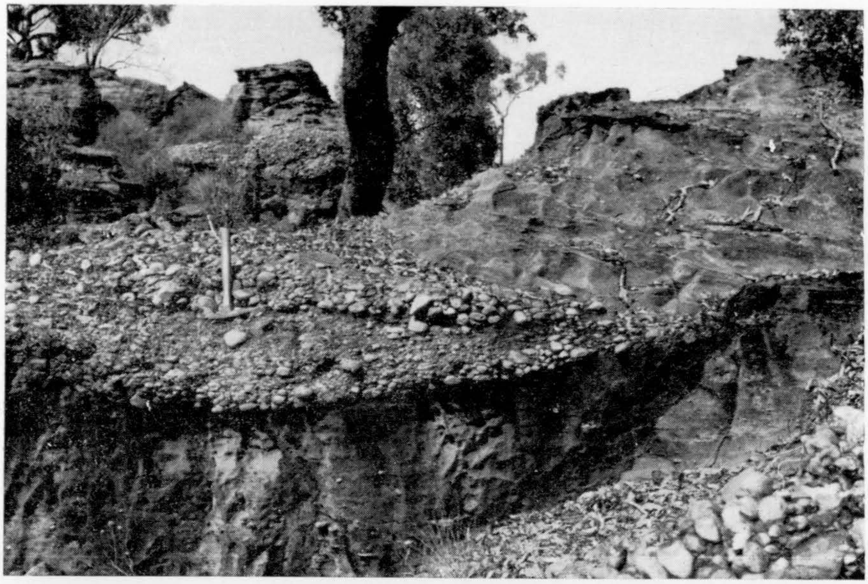


Plate 34, Figure 1. Lens of conglomerate in sandstone in the Border Creek Formation in the Weaber Range (locality 26-2)

Plate 34, Figure 2. Planed surface of conglomerate bed in Border Creek Formation at locality 400-8 in the Weaber Range. The conglomerate fills a trough in sandstone just above the disconformable contact with the Point Spring Sandstone. The Jacob Staff is 5 feet (150 cm) long is disconformably overlain by the basal conglomerate or basal sandstone of the Border Creek Formation. Two miles north of Mount Zimmermann, the Zimmermann Sandstone has been completely removed by erosion (Pl. 26, fig. 2; Pl. 27, fig. 1), and in the north-central Burt Range and at Mount Septimus the Border Creek Formation rests directly on the Septimus Limestone. In the southern part of the central Burt Range the Zimmermann Sandstone has been cut by a large channel at least 75 feet deep and erosion has reduced the thickness of the sandstone to about 100 feet, compared with 460 feet in the type section. The channel is filled with conglomerate of the Border Creek Formation (Pl. 26, fig. 1; Pl. 27, fig. 2).

Age

The composition of the fauna shows that the Zimmermann Sandstone is older than the Visean ($CuII_{\delta}$-$CuIII_{\alpha}$) Utting Calcarenite. By superposition, the sandstone is younger than the Septimus Limestone and hence its fauna is dated as uppermost Tournaisian to lowermost Visean.

Milligans Beds

Milligans Beds is the name given by G. A. Thomas (*in* Hare et al., 1961, unpubl.), in the completion report on the Spirit Hill No. 1 well, to the dark shale and siltstone in the subsurface of the Keep River Plain. The name has since been used by Veevers et al. (1964), and Guillaume (1966). Le Blanc (1964, unpubl., 1965, unpubl.), Duchemin & Creevey (1966, unpubl.), and Creevey (1966, unpubl.), however, broadened the use of the term to include all the Lower Carboniferous siltstone and shale in the Bonaparte and Kulshill wells. In this Bulletin we restrict the use of the name to the siltstone and shale on the platform (i.e. in the Milligans Hills/Spirit Hill area), and refer the Devonian and Carboniferous siltstone and shale in the deep wells to the Bonaparte Beds. According to our use of the term, the Milligans Beds are equivalent to a small part of the Bonaparte Beds.

The Milligans Beds are known from Milligans Nos 1 and 2 Bores at Milligans Hills, Spirit Hill Nos 1, 2, and 3 Bores on the southern margin of Spirit Hill, the Spirit Hill No. 1 well, and seismic shotpoints between Milligans Hills and Spirit Hill and around the Spirit Hill No. 1 well (see Map 1 and Table 1). Poor exposures identified as Milligans Beds have been mapped at Spirit Hill (Fig. 53). Dark shale and siltstone, correlated with the Milligans Beds on fossil evidence, are present in shothole samples in the Waggon Creek Valley, 7 miles southwest of Ningbing (P. J. Jones, BMR, pers. comm.).

The Milligans and Spirit Hill Bores were percussion holes and Spirit Hill No. 1 well was a continuously cored diamond drillhole. Samples from holes are held by the Bureau of Mineral Resources core and cuttings laboratory in Canberra.

Type Section. The beds between 146 and 510 feet in Milligans No. 1 at the southeastern corner of Milligans Hills at latitude 15°39′S., longitude 129°00½′E., are here chosen as the type section of the Milligans Beds (Fig. 49).

The Beds comprise grey to black silty shale which is locally calcareous, gypsiferous, or pyritic (Rade, *in* Utting, 1957, unpubl.). The shale is soft, fissile to blocky, and contains a rich microfauna and microflora as well as shell fragments, crinoid ossicles, and polyzoans.

In Milligans No. 1 the upper parts of Milligans Beds appear to be transitional with the overlying sandstone, siltstone, and sandy limestone, which we identify as Burvill Beds. However, because of the difference in age between the two formations (early Visean for the Milligans Beds, and late Visean for the Burvill Beds) there is a considerable hiatus (Fig. 40). Additional evidence in support of an hiatus is provided by the absence in Milligans No. 1 of the younger of two ostracod assemblages found in Milligans No. 2 (P. J. Jones, BMR, pers. comm.) Fossiliferous Burvill Beds consisting of ferruginized gritty limestone, calcareous sandstone, and quartz sandstone, crop out only 200 yards away from the bore site. The base of the Milligans Beds was not encountered in the bore.

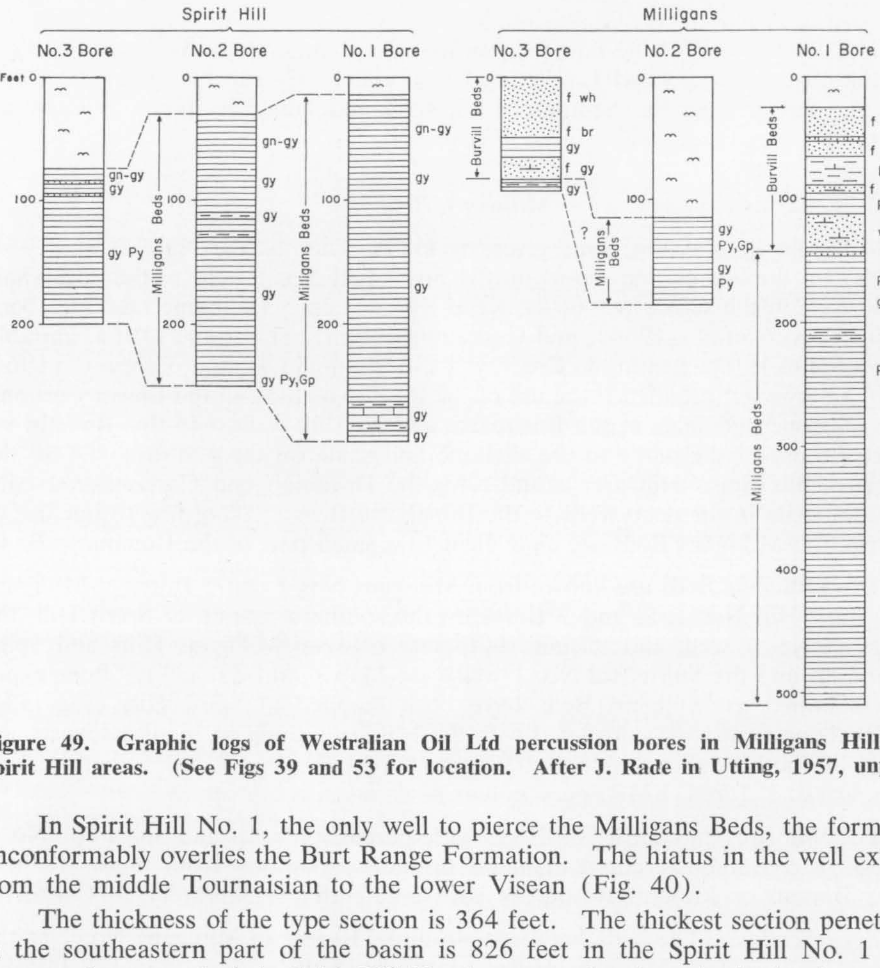


Figure 49. Graphic logs of Westralian Oil Ltd percussion bores in Milligans Hills and Spirit Hill areas. (See Figs 39 and 53 for location. After J. Rade in Utting, 1957, unpubl.)

In Spirit Hill No. 1, the only well to pierce the Milligans Beds, the formation unconformably overlies the Burt Range Formation. The hiatus in the well extends from the middle Tournaisian to the lower Visean (Fig. 40).

The thickness of the type section is 364 feet. The thickest section penetrated in the southeastern part of the basin is 826 feet in the Spirit Hill No. 1 well. Because the upper beds in Spirit Hill No. 1 are correlated on the basis of ostracods with the lower beds in Milligans No. 1 (P. J. Jones, BMR, pers. comm.), we estimate that the thickness of the formation is over 1,000 feet.

Other Sections. Spirit Hill No. 1 well, 1 mile north of Spirit Hill, began in Milligans Beds and passed through grey to black dolomitic shale with thin interbeds of sandstone and conglomerate to a depth of 826 feet (Fig. 54). At the base of the formation there is a pebble conglomerate containing rounded pebbles of quartzite and laths of siltstone and shale set in a matrix of coarse-grained quartz sandstone. The conglomerate unconformably overlies the Burt Range Formation. Microfossils have been found throughout, particularly at 50 feet and 99 feet; a spiriferoid brachiopod has been found in a conglomerate at 736 feet. Dr F. C. Loughnan (Univ. of NSW, pers. comm.), found that the shale had a slightly higher ratio of kaolinite to other clay minerals than that in Bonaparte No. 1. According to Loughnan this suggests that the Spirit Hill well is located nearer the margin of the basin, as independently indicated by pebble bands in the shale in the well. The Visean shale in Bonaparte No. 1 correlated with the Milligans Beds has a rich microfauna and a higher illite and lower kaolinite content. This is consistent with our view that the shale in the basinal province is marine and was deposited well away from the margins.

The Milligans No. 2 Bore, 2 miles northeast of Milligans Hills (Fig. 39), was drilled to a depth of 186 feet and penetrated unconsolidated sediments and 70 feet of Milligans Beds in the lower part of the hole. The shale contains two ostracod assemblages, the older of which is correlated with an assemblage in Milligans No. 1 (P. J. Jones, BMR, pers. comm.).

Only 8 feet of grey silty shale, tentatively identified as Milligans Beds, was encountered at the bottom of Milligans No. 3 Bore, which was drilled to a depth of 90 feet, 3 miles northeast of Milligans Hills. The shale is overlain by sandstone and shale, identified as Burvill Beds, which correlate lithologically with the rocks overlying the Milligans Beds in Milligans No. 1 (Fig. 49).

Three stratigraphic test holes, Spirit Hill Nos 1, 2, and 3 Bores, were drilled to the south of Spirit Hill (Fig. 53). The bores penetrated a sequence, identified as Milligans Beds, of virtually barren hard grey shale, which contains calcite, gypsum, and pyrite, and thin interbeds of sandy limestone and siltstone (Fig. 49).

Visean brachiopods have been collected from shale which probably lies stratigraphically above that in the Spirit Hill bores, at locality 73, 1 mile west of Spirit Hill No. 1 Bore (Fig. 53). The outcrops at Spirit Hill are described on page 101.

Palaeontology

The fossils found in the Milligans Beds include ostracods, foraminifers (including endothyrids), conodonts, small pelecypods, immature brachiopods, crinoid columnals, gastropods, echinoid spines and tubercles, polyzoans, holothurian sclerites, fish scales, scolecodonts, tracheid plant fragments, and spores. Most of the macrofossils are small, probably stunted specimens.

P. J. Jones (BMR, pers. comm.) notes that the Milligans No. 1 Bore lacks foraminifers, but has abundant brachiopods, gastropods, pelecypods, crinoids, and echinoids, whereas the fauna from the BMR seismic shotholes north of Spirit Hill is rich in foraminifers and holothurian and fish remains.

In the Spirit Hill No. 1 well rare microfossils, including foraminifers, ostracods, scolecodonts, and megaspores, have been recovered from throughout the shale, particularly at 50 and 99 feet, and a brachiopod at 736 feet. Balme (*in* Hare et al., 1961, unpubl.) identified a large microflora from the well.

The most useful fossils are the ostracods and foraminifers. P. J. Jones (BMR, pers. comm.) has recognized two assemblages of ostracods from the Milligans bores. Both ostracods and foraminifers have enabled correlation between Milligans No. 2 Bore and core 9 from Bonaparte No. 1 well.

On the basis of a distinctive ostracod assemblage, the lower part of the shale penetrated by Milligans No. 2 Bore is correlated with the entire shale sequence in Milligans No. 1 (P. J. Jones, BMR, pers. comm.). Some of the species in this assemblage have been found at a depth of 50 feet in the Milligans Beds in the Spirit Hill No. 1 well; they indicate the correlation of the top part of the section in the well with the bottom part of that in Milligans No. 1. This correlation is contrary to Balme's suggestion (*in* Hare et al., 1961, unpubl.), based on the microflora, that the shale in the upper part of Spirit Hill No. 1 well can be correlated with the interval between 191 and 392 feet (the middle part) of Milligans No. 1.

A second ostracod assemblage at the top of the shale in Milligans No. 2 Bore indicates a correlation with the shale in BMR shot points in Waggon Creek valley, southwest of Ningbing, and with shale in core 9 at 2,500 feet in the Bonaparte No. 1 well.

Age

The microfossils from Milligans No. 2 Bore are the same as those in core 9 of the Bonaparte No. 1 well, and have been dated by D. J. Belford (BMR, pers. comm.) as Visean. Because cores 6 to 8 from Bonaparte No. 1 are correlated with the lower to middle Visean ($CuII_\delta$-$CuIII_\alpha$) Utting Calcarenite, the Milligans Beds are dated as probably lower Visean. Brachiopods from locality 73 on the southern margin of Spirit Hill are younger than those in the Zimmermann Sandstone, also indicating a Visean age.

The relationships between the Milligans Beds and the formations in the Burt Range area cannot be determined from outcrop. Because the Milligans Beds unconformably overlie the Burt Range Formation in the Spirit Hill No. 1 well, and because wherever they are fossiliferous they have been dated as Visean, we consider them to be younger than the Zimmermann Sandstone, and to overlie, probably unconformably, the Burt Range Formation, Enga Sandstone, Septimus Limestone, and Zimmermann Sandstone (Fig. 38).

Border Creek Formation in the Burt Range Area

The general description of the Border Creek Formation, of probable Upper Carboniferous age, is given on page 108.

The Border Creek Formation is the youngest rock unit in the Burt Range area and comprises the sandstone, siltstone, and conglomerate capping the central Burt Range, Mount Septimus, Milligans Hills, and the western part of Spirit Hill. An isolated outcrop has been mapped on the southern margin of the Burt Range Amphitheatre (Fig. 39).

In the Burt Range area the Border Creek Formation is expressed as high cliffs of jointed sandstone and conglomerate separated by deep undercuts exposing soft siltstone. On the air-photographs the formation is seen to be well layered (Pl. 22); in the southern part of the central Burt Range and the western part of Spirit Hill the sandstone exhibits a strong system of joints and is weathered into beehive-shaped turrets (Pl. 28, fig. 1).

Border Creek Disconformity. The Border Creek disconformity is the only regional break in the Carboniferous of the southern Bonaparte Gulf Basin. In the Burt Range area, which structurally is a syncline, the Border Creek Formation disconformably overlies the Burvill Beds, Milligans Beds, Septimus Limestone, Zimmermann Sandstone, and Enga Sandstone (Fig. 50). Figure 50 shows that erosion was greater on the flanks, particularly the eastern flank, than in the central part of the syncline, where part of the Zimmermann Sandstone was preserved. In the Weaber Range the greatest thickness of Point Spring Sandstone, which underlies the Border Creek Formation, is in the middle of the range and may also mark the axis of a syncline (Fig. 50).

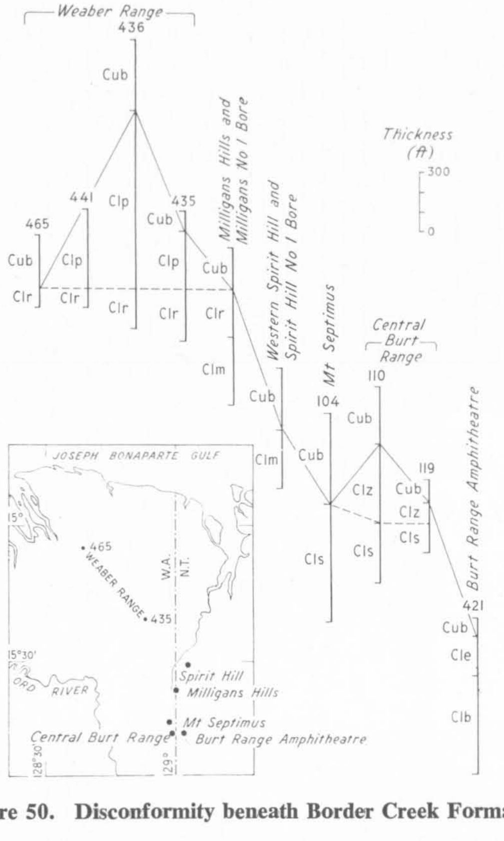


Figure 50. Disconformity beneath Border Creek Formation

Before the Border Creek Formation was laid down in the south-central Burt Range the Zimmermann Sandstone was deeply channelled by erosion and completely stripped from the northern part of the range to expose the Septimus Limestone. The northernmost part of the Zimmermann Sandstone appears to have been truncated by a channel in the erosion surface, which was later filled by the basal sandstone of the Border Creek Formation. The contact between the two formations in the channel is obscured by talus. Plates 26(1) and 27(2) show the jointed sandstone bed overlying the thinly bedded Zimmermann Sandstone, which rapidly thickens so that the sandstone of the Border Creek Formation rests against the eroded surface of the Zimmermann Sandstone. This could be interpreted as a lateral change from a deposit of well sorted fossiliferous fine-grained sandstone to a contemporaneous channel deposit of poorly sorted barren coarse-grained sandstone. However, because the sandstone in the channel is part of the same bed that overlies the Zimmermann Sandstone we consider it is Border Creek Formation.

Sections. In section 110, on the western scarp of the central Burt Range, the Border Creek Formation crops out in the interval from 835 to 1,120 feet above the base, and overlies the type section of the Zimmermann Sandstone (Fig. 47; Pl. 25, fig. 2). The base of the Border Creek Formation is taken at the first conglomerate in the scarp; the top is eroded.

The formation comprises interbedded sandstone, siltstone, and conglomerate. The sandstone is a moderately to poorly sorted medium to coarse-grained feldspathic quartz sandstone with a clay cement. It is usually laminated in thick beds and is locally cross-bedded. The sandstone is white to brown near the base of the formation and becomes ferruginized towards the top of the range.

The siltstone is frequently laminated, white when freshly exposed, and yellow, purple, or red when weathered.

The conglomerate (Pl. 28, fig. 2) contains pebbles of rounded to subrounded quartzite which average 2 inches in diameter but range up to 6 inches, fewer laths of Precambrian siltstone, and mud pellets, set in a matrix of poorly sorted coarse-grained quartz sandstone; it is locally cross-bedded. The conglomerates usually overlie eroded surfaces and wedge out over short distances. When traced southwards from section 110 the basal conglomerate fills a deep channel cut in the underlying Zimmermann Sandstone (Pl. 26, fig. 1; Pl. 27, fig. 2). The channel, immediately east of Langfield Point, is about 1,500 feet wide, up to 75 feet deep at the centre, U-shaped in cross-section, and is expressed topographically as a hollow in the southern part of the range. The clasts in the conglomerate of the channel are mainly rounded to subrounded quartzite boulders which average 4 inches in diameter but range up to 1 foot; minor clasts of quartz sandstone and large blocks of siltstone, up to 15 feet by 8 feet, are also present. The conglomerate lenses out to the north of section 110 and in less than 2 miles it gives way to sandstone.

At Mount Septimus, the Septimus Limestone is overlain by medium to coarse-grained buff to white feldspathic quartz sandstone, siltstone, and conglomerate. A conglomerate, 65 feet thick, in section 150 at the southern end of the mountain wedges out within a mile to a pebble band in section 104. A second conglomerate in section 104 fills channels in the top of a siltstone, but is also present as lenses in the siltstone (Fig. 51), which suggests closely associated deposition in a stream or lake.

At Milligans Hills the Border Creek Formation overlies coarse brown calcareous sandstone of the Burvill Beds. In section 147, in the westernmost hill (Fig. 52), the Burvill Beds are overlain by 15 feet of barren, medium-grained grey-brown quartz sandstone identified as Border Creek Formation. The sandstone is overlain by a conglomerate containing rounded to well rounded quartzite pebbles ranging from 2 inches to 1 foot in diameter set in a matrix of coarse-grained ferruginous sandstone.

A similar conglomerate, 35 feet thick, crops out in the northernmost hill (Fig. 52, section 155) and is overlain by 100 feet of thick-bedded coarse to medium-grained brown feldspathic quartz sandstone and 10 feet of pebbly sandstone which crop out as steep cone-shaped turrets (Pl. 29, fig. 1).

The Border Creek Formation in the western part of Spirit Hill is described on page 101.

Farther northeastward, the Border Creek Formation crops out northwest of Alpha Hill (Pl. 29, fig. 2).

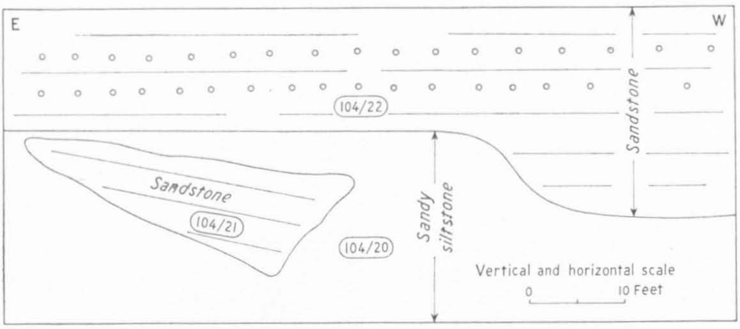


Figure 51. Sketch section at locality 104/20-22, Mount Septimus, showing cut-and-fill sandstone structure in sandy siltstone of Border Creek Formation

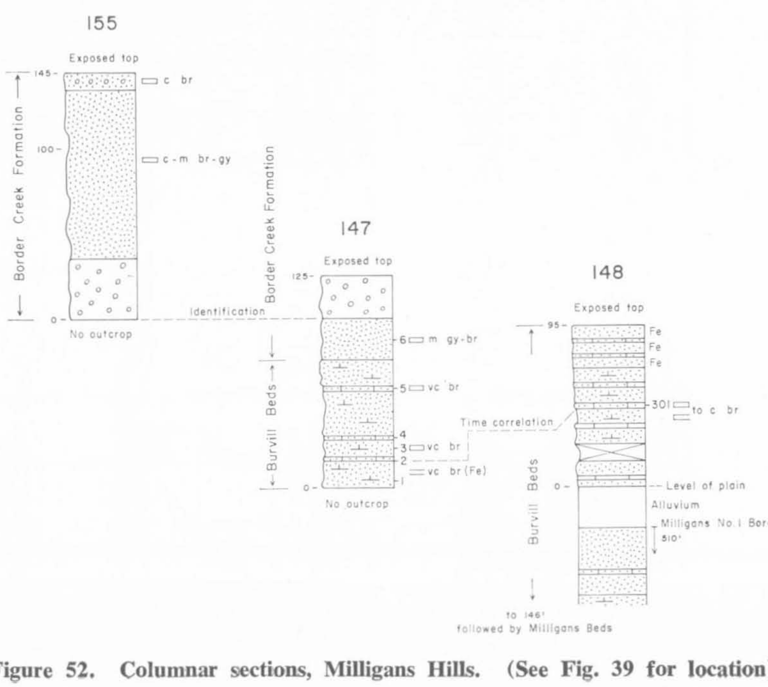


Figure 52. Columnar sections, Milligans Hills. (See Fig. 39 for location)

SPIRIT HILL AREA

Spirit Hill is the name given to a group of hills rising about 600 feet above a tree-covered plain 14 miles north of the central Burt Range and 8 miles east of the Pincombe Range. The hills are close to the eastern margin of the basin (Pls 30, 31).

Traves (1955) assigned all of the rocks in the Spirit Hill area to the Weaber Group. He proposed the name Spirit Hill Limestone for the sandy limestone and calcareous sandstone on the southeastern part of the hill, and considered them to be Permian. He also described scattered outcrops of Spirit Hill Limestone between Spirit Hill and the Legune track crossing at Sandy Creek.

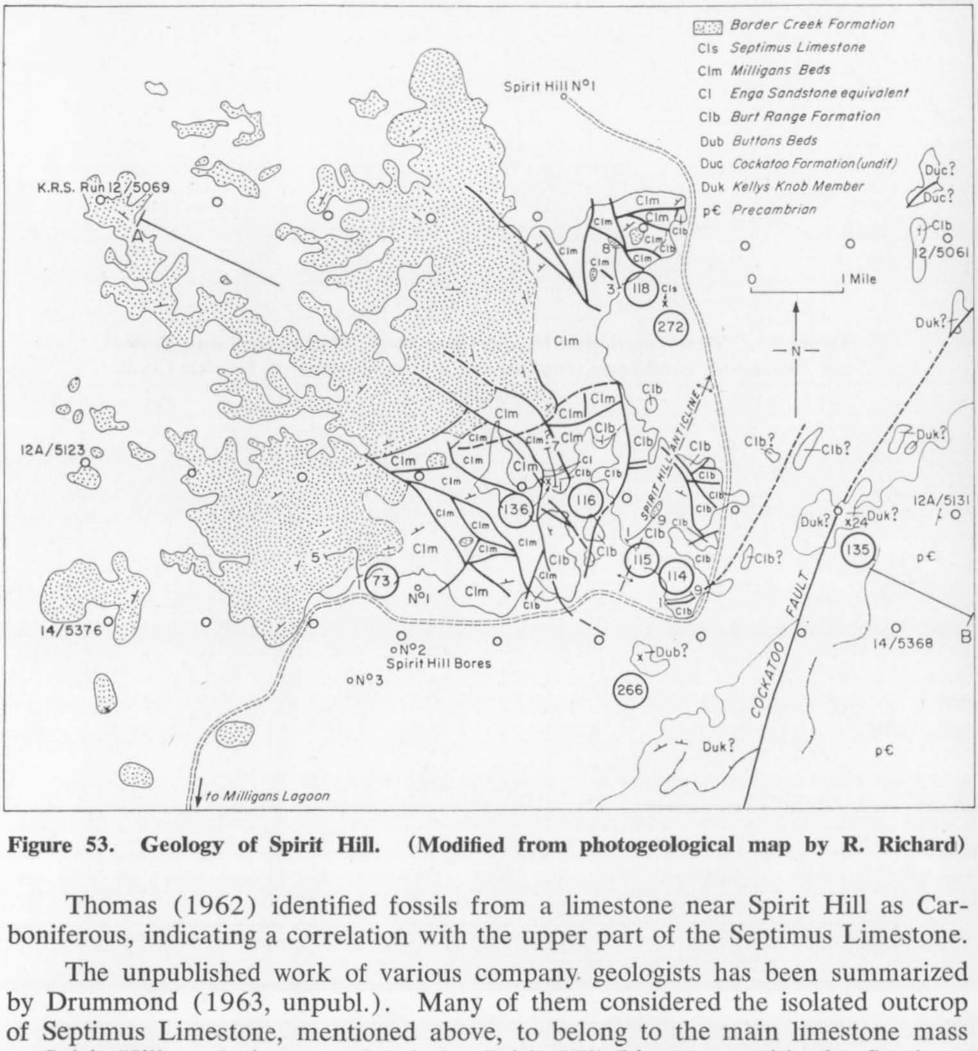


Figure 53. Geology of Spirit Hill. (Modified from photogeological map by R. Richard)

Thomas (1962) identified fossils from a limestone near Spirit Hill as Carboniferous, indicating a correlation with the upper part of the Septimus Limestone.

The unpublished work of various company geologists has been summarized by Drummond (1963, unpubl.). Many of them considered the isolated outcrop of Septimus Limestone, mentioned above, to belong to the main limestone mass at Spirit Hill, and thus correlated the Spirit Hill Limestone with the Septimus Limestone. This led to a misinterpretation of the geology and of the sequence in the Spirit Hill No. 1 well (see Drummond, 1963, fig. 7) about 1 mile north of

Spirit Hill. Palaeontological work has shown that with one exception the carbonate rocks at Spirit Hill and in Spirit Hill No. 1 between 826 and 2,000 feet correlate with part of the Burt Range Formation. The term Spirit Hill Limestone is thus a junior synonym of the Burt Range Formation and is discarded.

Outline of the Geology of Spirit Hill

The distribution of the formations exposed at Spirit Hill is shown in Figure 53. Six formations have been recognized in outcrop; in ascending stratigraphic order they are: the Buttons Beds(?), the Burt Range Formation, an unnamed limestone equivalent to the basal part of the Enga Sandstone, the Septimus Limestone, the Milligans Beds, and the Border Creek Formation. Three of the formations are present in Spirit Hill No. 1, which was drilled to a depth of 3,003 feet (Fig. 54).

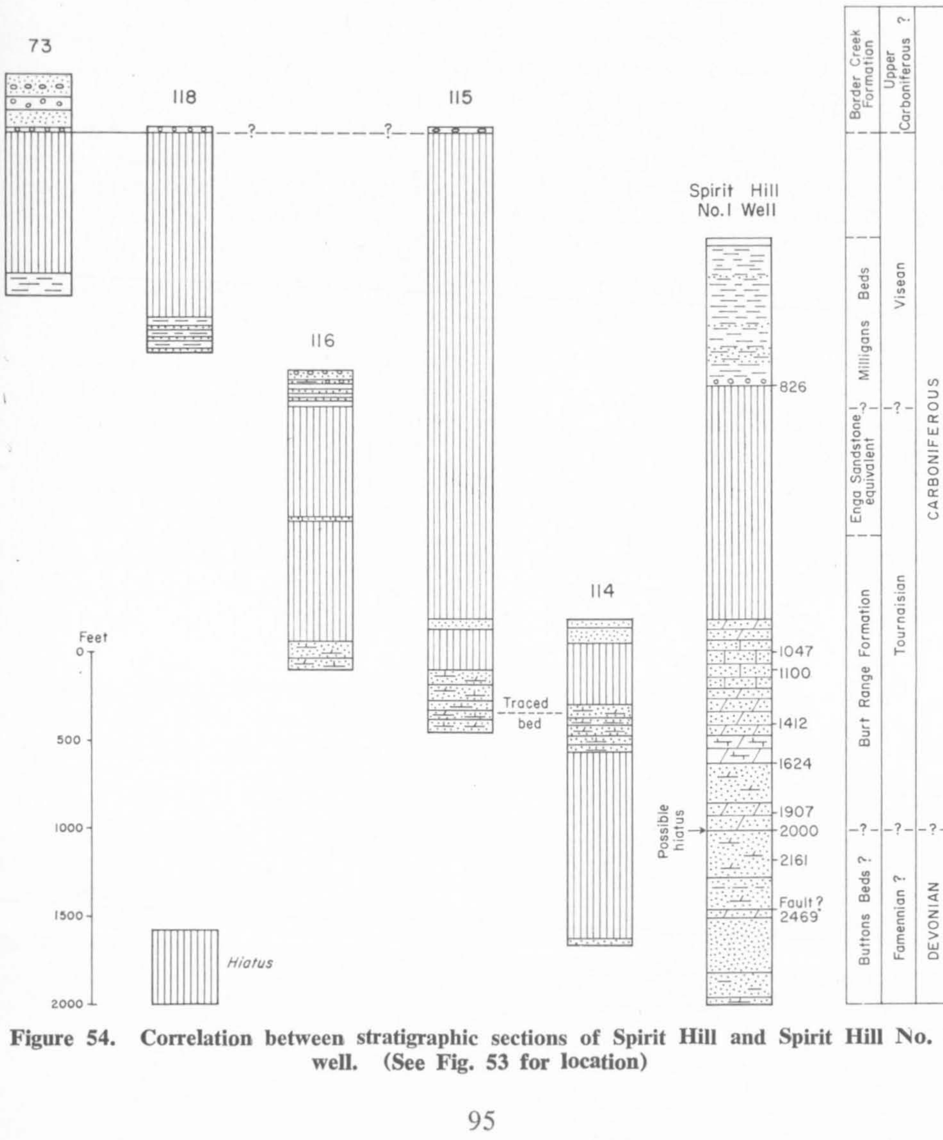


Figure 54. Correlation between stratigraphic sections of Spirit Hill and Spirit Hill No. 1 well. (See Fig. 53 for location)

Spirit Hill can be divided into three topographical units: a complex series of hills and amphitheatres in the southeast; lower, more rounded, grass-covered hills in the northeastern and central regions; and blocky hills, many deeply dissected, to the west. The units have different outcrop patterns on the air-photographs and correspond to the main formations cropping out on Spirit Hill (Fig. 53; Pl. 30). The Burt Range Formation, in the southeastern corner, has a well layered pattern which contrasts with the smooth appearance of the Milligans Beds in the northeastern and central part. To the west, the sandstone in the Border Creek Formation has a regular joint system.

The small outcrops, tentatively identified as Buttons Beds, on the southeastern part of Spirit Hill are overlain, probably unconformably, by the Burt Range Formation. The Buttons Beds(?) consist of coarse-grained quartz sandstone containing pelecypods and plant remains.

The Burt Range Formation consists dominantly of calcareous and dolomitic sandstone with minor quartz sandstone and sandy limestone. It has been subdivided into three informal stratigraphic units usually separated by unconformities in the southeastern part of Spirit Hill. The rocks are more sandy and more dolomitic than their equivalents in the type section and are lithologically similar to those in the Burt Range Amphitheatre. The stratigraphic relationships with other sections through the Burt Range Formation are shown in Figure 43.

An unnamed grey crinoidal sandy limestone, equivalent to the basal part of the Enga Sandstone, unconformably overlies the Burt Range Formation in section 116 (Fig. 53).

Elsewhere, the Burt Range Formation is unconformably overlain by a poorly exposed sequence of shale, sandstone, calcareous sandstone, and conglomerate referred to the Milligans Beds. The best outcrops are at locality 118 (Fig. 53) in northeastern Spirit Hill, and at locality 73 on the southern margin of the hill, where grey silty shale is interbedded with sandstone. The shale is not well exposed elsewhere.

The Border Creek Formation crops out over the whole of the western part of Spirit Hill and extends as tongues and outliers into the eastern part of the hill where it unconformably overlies the Milligans Beds and the Burt Range Formation.

The Septimus Limestone is shown from a single isolated outcrop at locality 272, just east of Spirit Hill. It has not been found on the main hill, and its exact stratigraphic relationship with the other formations at Spirit Hill is not clear.

Structure

The structure of Spirit Hill has not been studied in detail, but a photogeological interpretation by R. Richard (Fig. 55) shows that it is extensively faulted in the east and that some of the larger faults have extended westwards into the Border Creek Formation. A cross-section (Fig. 56) through Spirit Hill shows that it is a faulted anticline. The axis of the anticline, in the southeastern part of the hill, trends 025° and pitches towards the northeast. Folding may have initially taken place as early as the lower or middle Tournaisian. The anticline can be seen in a panorama of southeastern Spirit Hill.

Traves (1955) mapped an anticline and syncline at Spirit Hill, but we could not recognize these folds. The anticlinal axis on our map is essentially the same as that recognized by Allen (1956, unpubl.); a copy of Allen's map is given by Drummond (1963, fig. 5, unpubl.).

The major fault between the Precambrian and Palaeozoic sediments, east of Spirit Hill, has a throw of over 4,000 feet; it does not crop out and its position on the cross-section (Fig. 56) is inferred. Major faulting took place after the deposition of the Border Creek Formation, that is, after the Upper Carboniferous.

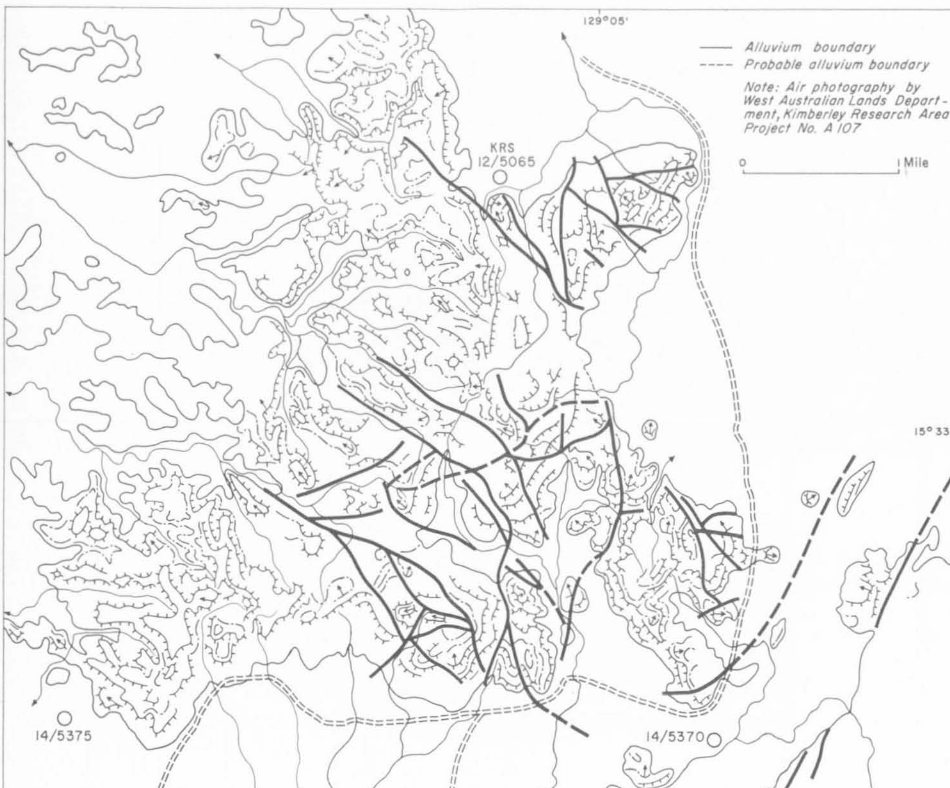


Figure 55. Photogeological map of Spirit Hill (by R. Richard)

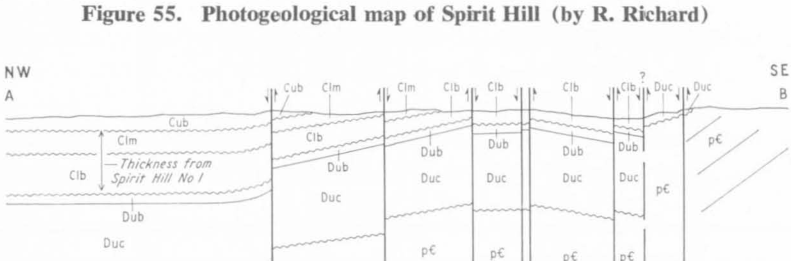


Figure 56. Cross-section at Spirit Hill. (See Fig. 53 for location)

Figure 53 shows that most of the smaller faults affect the Devonian and Lower Carboniferous formations in the eastern part of Spirit Hill, but not the Upper Carboniferous Border Creek Formation in the west. We therefore infer that most of the minor faulting took place after the deposition of the lower Visean Milligans Beds (Fig. 57). However, some earlier faulting probably took place when the Spirit Hill area was folded, and may have been responsible for a number of the unconformities. Downfaulting in the late Tournaisian or early Visean was probably responsible for the preservation of the Septimus Limestone at locality 272, immediately east of Spirit Hill.

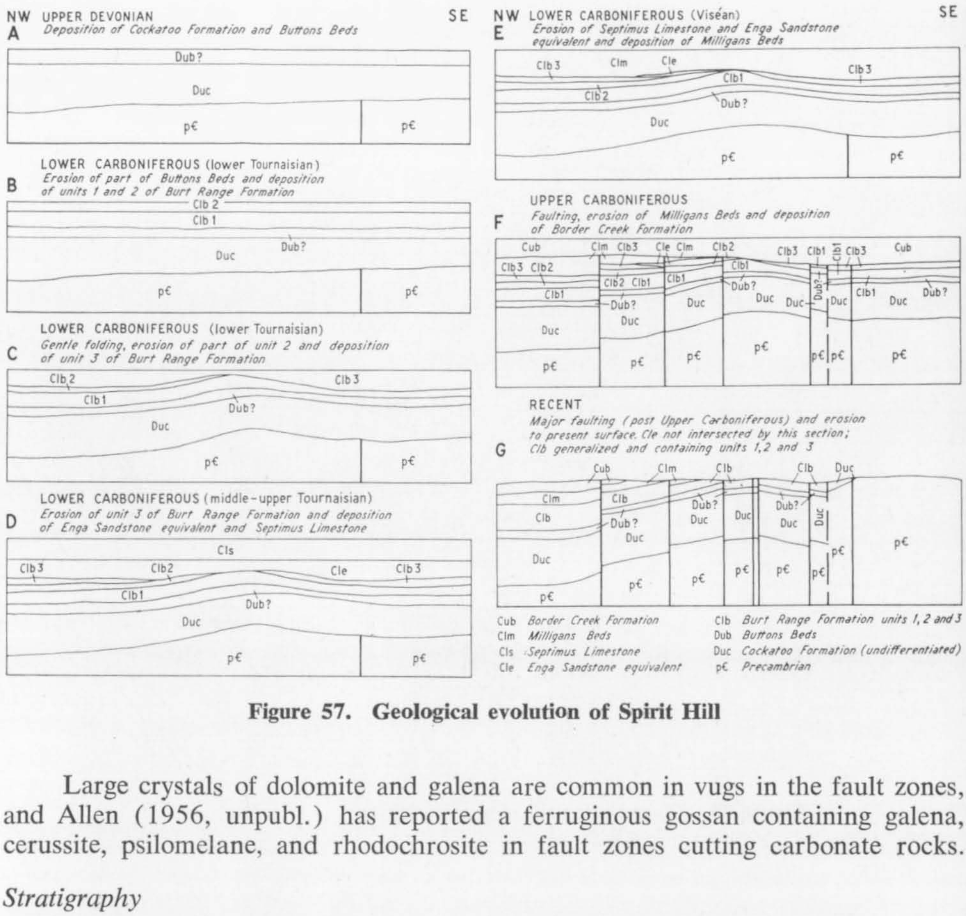


Figure 57. Geological evolution of Spirit Hill

Large crystals of dolomite and galena are common in vugs in the fault zones, and Allen (1956, unpubl.) has reported a ferruginous gossan containing galena, cerussite, psilomelane, and rhodochrosite in fault zones cutting carbonate rocks.

Stratigraphy

Southeastern Spirit Hill Area. Sections 114, 115, and 116 (Fig. 53) were measured in the southeastern part of Spirit Hill. Columnar sections are given in Figure 58, and Figure 54 shows the stratigraphic relationships between the sections and the sequence in the Spirit Hill No. 1 well; it also shows five unconformities in the area. The lowermost unconformity separates the Buttons Beds(?) and Burt Range Formation; the second is within the Burt Range Formation; the third separates the Burt Range Formation and an unnamed limestone equivalent to the base of the Enga Sandstone; the fourth occurs between the Burt Range Formation and Border Creek Formation; and there is probably a fifth unconformity between the Burt Range Formation and Milligans Beds. The hiatus at each break is illustrated diagrammatically in Figure 54.

At the base of section 114, 25 feet of barren thick-bedded coarse-grained white quartz sandstone is tentatively identified as Upper Devonian Buttons Beds. A similar sandstone, half a mile south of the section line at locality 266, contains logs of *Leptophloeum australe* (M'Coy) and pelecypods; the pelecypod fauna is the same as that in interbedded sandstone and limestone, mapped as Buttons Beds, at locality 146/4 near Eight Mile Creek (Fig. 39).

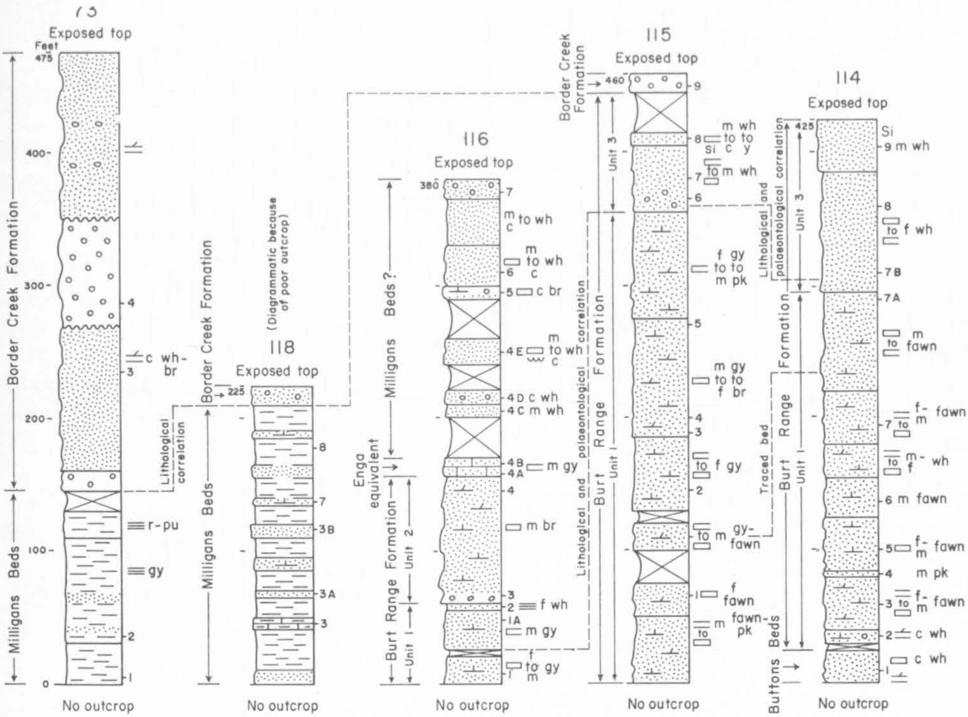


Figure 58. Columnar sections at Spirit Hill. (See Fig. 53 for location)

Overlying the sandstone in section 114, probably unconformably, is 265 feet of fine to medium-grained fawn dolomitic and calcareous sandstone belonging to the Burt Range Formation.

Three rock units (not formally named) have been recognized in the Burt Range Formation. They are virtually the units mapped by Allen (1956, unpubl.), whose geological map of Spirit Hill has been reproduced by Drummond (1963, unpubl.).

Unit 1 consists of medium to thick-bedded fine to medium-grained grey to fawn dolomitic and calcareous sandstone. It crops out in alternating hard and soft bands and in places forms small cliffs (Pl. 31). Fossils are common in the upper part of the unit, as for example at localities 114/7A and 115/4; they indicate equivalence with the middle part of the Burt Range Formation in the type area, probably with the interval between 800 and 900 feet.

Unit 2 is a dark brown dolomitic and calcareous sandstone with a pebble bed at the base; the pebbles are rounded and consist of quartzite and milky quartz ranging from 1 to 2 inches in diameter, with a few up to about 5 inches. The brown calcareous sandstone is medium-grained, thickly bedded, and forms prominent cliffs. The best exposures are in section 116 on the northern part of the hill (Fig. 53). The fossils are very poorly preserved (loc. 116/3), and like those of unit 1, indicate equivalence with the middle part of the Burt Range Formation.

Unit 3 is a medium to thickly bedded medium to fine-grained white quartz sandstone which is silicified in places. Rounded pebbles of quartzite up to 2 inches in diameter are present at the base of the unit in section 115. The fossils from unit 3 (locs 114/7B & 115/7) indicate the same age as those from units 1 and 2.

In sections 114 and 115, the grey to fawn calcareous sandstone of unit 1 is disconformably overlain by white quartz sandstone of unit 3 (Pl. 31). By tracing a bed between the two sections it can be shown that the uppermost 180 feet of calcareous sandstone in section 115 is missing in section 114. The disconformity can be seen on the southern part of the hill, where white sandstone is at the same level as the calcareous sandstone in the northern part of the hill (Pl. 31, Fig. 1). The possibility that the southernmost sandstone outcrop is a lateral equivalent of part of the calcareous sandstone is rejected because of an angular difference between units 1 and 3 in section 114. In this section the calcareous sandstone dips 5° at 065° and the white sandstone is horizontal; no angular difference was seen in section 115. This particular disconformity is apparent only in sections 114 and 115 on the western and southern parts of the hill (Fig. 53). In the north, the grey to fawn calcareous sandstone of unit 1 is overlain, apparently conformably, by a dark brown calcareous sandstone of unit 2, which is overlain, again apparently conformably, by white quartz sandstone of unit 3.

The fossils from above and below the disconformity are short-ranging and are restricted to the 800 to 900-foot interval in the type section of the Burt Range Formation, which suggests that there was only a short hiatus.

In section 116 dark brown calcareous sandstone of unit 2 is paraconformably overlain by a thin, unnamed, grey sandy limestone which, from faunal evidence, is equivalent to the basal part of the Enga Sandstone.

Overlying the unnamed limestone is a succession of quartz sandstone, calcareous sandstone, and conglomerate. The sandstone is a white medium to coarse-grained quartz sandstone and contains a few pectinid pelecypods at locality 136/2, near the base (Fig. 53). At 300 feet in section 116 there is a very coarse-grained brown calcareous sandstone and conglomerate (Pl. 32, fig. 1). The conglomerate contains rounded pebbles of quartzite ranging from 0.5 to 3 inches in diameter, subangular blocks of limestone up to 6 inches long, and laths of Precambrian siltstone set in a matrix of coarse-grained brown calcareous sandstone. The loose yellow marl observed in the unexposed intervals in section 116 is thought to indicate the presence of shale interbeds; similar marl has been collected from the shaly parts of section 118 in the northeastern Spirit Hill area.

This succession is tentatively identified as Milligans Beds because it has the same outcrop pattern and contains the same rock types as that identified as Milligans Beds in the northeastern part of Spirit Hill. However, because of the age of the underlying limestone (basal Enga Sandstone) the succession could be a lateral equivalent of the Enga Sandstone. The fossils from locality 136/2 are not sufficiently diagnostic to provide a correlation.

A conglomerate at the top of section 115, identified as Border Creek Formation, rests unconformably on the Burt Range Formation (unit 3).

Northeastern Spirit Hill Area. In the northeastern part of Spirit Hill the Burt Range Formation is overlain, probably unconformably, by sediments identified as Milligans Beds. The beds are in turn unconformably overlain by a thin capping of Border Creek Formation. An isolated outcrop of Septimus Limestone has been mapped at locality 272 (Fig. 53).

Outcrops of the Milligans Beds consist mainly of tumbled blocks of sandstone and soft interbedded shale. One fairly well exposed section in a gully at locality 118 (Fig. 53) comprises a succession of grey silty shale containing beds of marl, sandstone, and calcareous sandstone. A diagrammatic representation of this section is given in Figure 58. The sandstone is generally a well sorted medium-grained white quartz sandstone which has probably been leached. It is frequently ripple-marked, exhibits sole marks and flute casts, and contains mud pellets. Some poorly preserved brachiopods and gastropods have been found in a sandstone at locality 118/3, midway up the section, and fragments of fossil wood have been collected from throughout the section. A stem from locality 118/7 has been identified by Mary E. White (*in* BMR Record 1966/113) as *Lepidodendron* sp. cf. *L. veltheimianum* Sternberg.

The Septimus Limestone at locality 272 consists of a low mound of fossiliferous calcarenite. Thomas (1962) has shown that the brachiopod fauna from this locality is equivalent in age to his assemblage 'a' at the top of the Septimus Limestone.

Western Spirit Hill Area. On the southern margin of the western part of Spirit Hill, at locality 73 (Fig. 53), shale of the Milligans Beds is unconformably overlain by the Border Creek Formation. The Milligans Beds comprise fissile blue-grey shale containing occasional resistant silty bands and beds of fontainebleau sandstone, overlain by red to purple shale. Brachiopods from the harder silty beds at locality 73/2 indicate a Visean age. The shale is probably the same as that, dated as Visean (Jones *in* Thomas, 1962), in the Milligans Hills Nos 1 and 2 Bores near Milligans Lagoon (Fig. 39).

The Border Creek Formation is exposed in high turreted cliffs along the southwestern and western parts of Spirit Hill (Pl. 28, Fig. 1) and extends as scattered outcrops to Milligans Hills, 3 miles to the southwest. The basal beds in section 73 (Fig. 58) consist of boulder and cobble conglomerate with poorly rounded quartzite, sandstone, and crystalline(?) fragments up to $1\frac{1}{2}$ feet in diameter set in a matrix of coarse feldspathic quartz sandstone. The basal conglomerate is overlain by a coarse-grained cross-bedded white to fawn feldspathic quartz sandstone containing several layers of pebbles and boulders. Channels up to a foot deep have been cut into the top of the sandstone and filled by the overlying conglomerate. The conglomerate contains fragments of quartzite, sandstone, and white siltstone averaging 5 inches in diameter, with the largest about 3 feet across. The matrix is similar to the underlying sandstone. Allen (1956, unpubl.) recorded angular blocks of purple to grey indurated mudstone up to 6 feet long lying parallel with the bedding planes of the same conglomerate in the southwestern part of Spirit Hill. At the top, the conglomerate has also been channelled and filled with coarse feldspathic quartz sandstone containing pebble bands. Both sandstone units in the conglomerate are cut by intersecting vertical joint systems (Pl. 28, fig. 1; Pl. 32, fig. 2) and are weathered into high beehive-shaped turrets.

Spirit Hill No. 1 Well. Spirit Hill No. 1 is a continuously cored diamond drillhole, 3,003 feet deep, about 1 mile north of Spirit Hill (Table 1; Fig. 53). The completion report on the well by R. Hare et al. (1961, unpubl.) was revised by G. A. Thomas (1961, unpubl.). Drummond (1963, unpubl.) re-examined the Spirit Hill No. 1 core, gave detailed lithological descriptions (Drummond, app. 5) and showed various stratigraphic interpretations of the well (Drummond, fig. 7). A slightly modified columnar section, taking into account the information from the completion report and the later work of Drummond, is given in Figure 54. The section shows the main rock types, a break in sequence, and the formations to which the rocks have been assigned.

The shale to a depth of 826 feet is identified as Milligans Beds. P. J. Jones (BMR, pers. comm.) has correlated an ostracod assemblage from a depth of 50 feet with a similar assemblage towards the base of Milligans No. 1 Bore. Balme (1961), in the revised completion report on Spirit Hill No. 1, identified spores from several samples of shale and found the assemblage to be closely comparable with that from the Milligans No. 1 Bore; he suggested that the shales in both bores could be correlated. Jones dated the shales in Spirit Hill No. 1 well and Milligans Nos 1 and 2 Bores as Visean.

The sequence between 826 and 2,000 feet is identified as Burt Range Formation. Both brachiopods (J. Roberts) and conodonts (E. C. Druce, BMR) show that the top of the Burt Range Formation in the well can be correlated with the interval between 800 and 900 feet in the type section, dated as lower to middle Tournaisian (Jones & Druce, 1966). Together with the presence of a pebbly conglomerate at the base of the Milligans Beds, this indicates that there is an hiatus between the Milligans Beds and the Burt Range Formation in Spirit Hill No. 1.

The section between 826 and 1,300 feet can be correlated with the top of unit 1 and units 2 and 3 of the Burt Range Formation in the southeastern Spirit Hill area. The base of the Burt Range Formation is drawn at a depth of 2,000 feet because conodonts from 1,907 feet indicate a correlation with locality 100/6A (E. C. Druce, BMR, pers. comm.), from just above the base of the formation in the type section (Fig. 41); ostracods from 1,907 feet suggest a slightly higher equivalent, 300 feet above the base of the Burt Range Formation. Few brachiopods have been found between 1,400 and 2,000 feet in the well. Those from 1,413 feet correlate with a similar assemblage between 400 and 500 feet above the base of the type section.

The rocks beneath 2,000 feet are mainly sandstone and dolomitic sandstone and are possibly Devonian in age and tentatively identified as Buttons Beds. G. A. Thomas (*in* Hare et al., 1961) identified a specimen of *Leptophloeum australe* (M'Coy) from a depth of 2,161 feet and a 'cosmoid' fish scale from a depth of 2,564 feet. Both fossils are common in the Upper Devonian, but are also known in the Lower Carboniferous. No other palaeontological evidence is available.

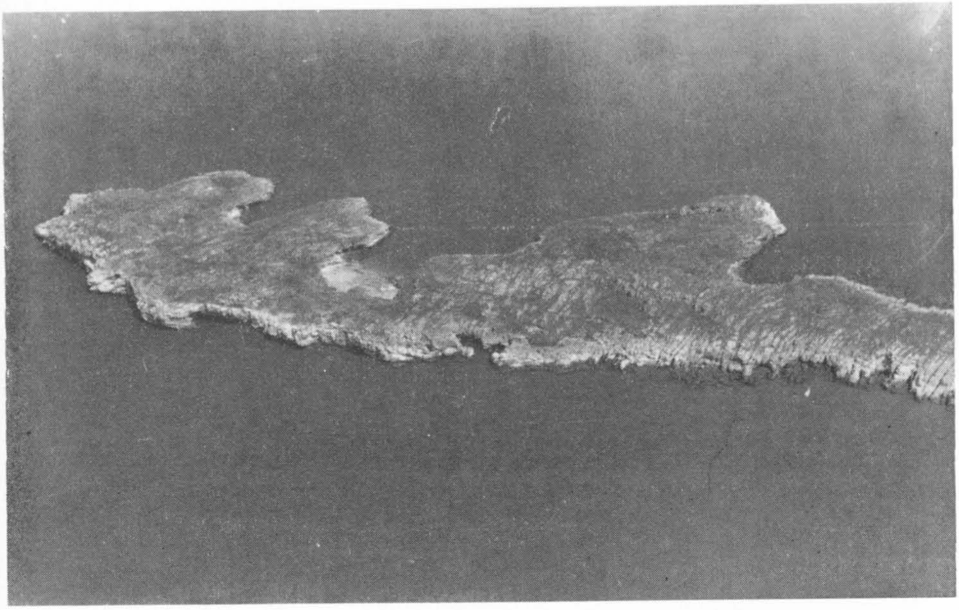


Plate 35, Figure 1. Rocky islet, seen from the northeast, at mid-tide. For details, see Figure 62

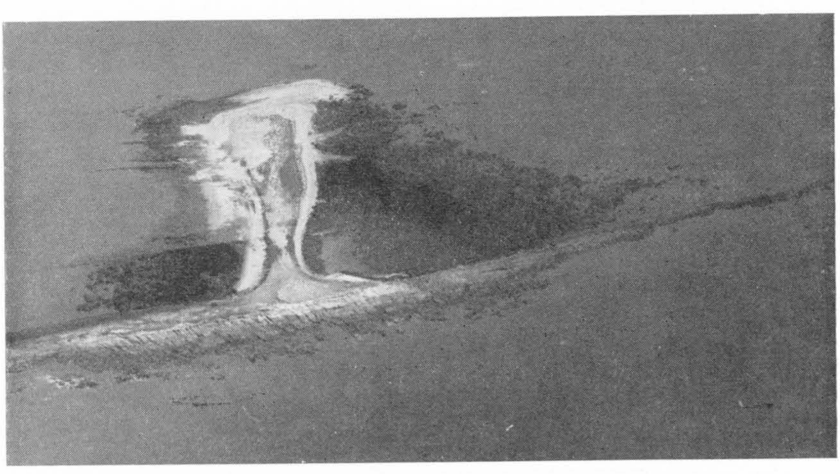


Plate 35, Figure 2. Pelican Islet, seen from the north, at mid-tide. For details, see Figure 62

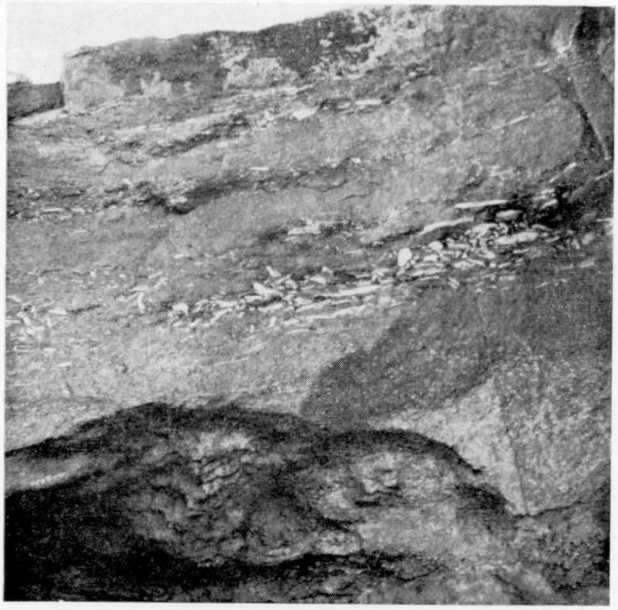


Plate 36, Figure 1. Platy fragments of white siltstone in sandstone of probable Border Creek Formation. Sea-stack off eastern tip of Rocky Islet (locality 433-1). The largest fragment is about 6 inches

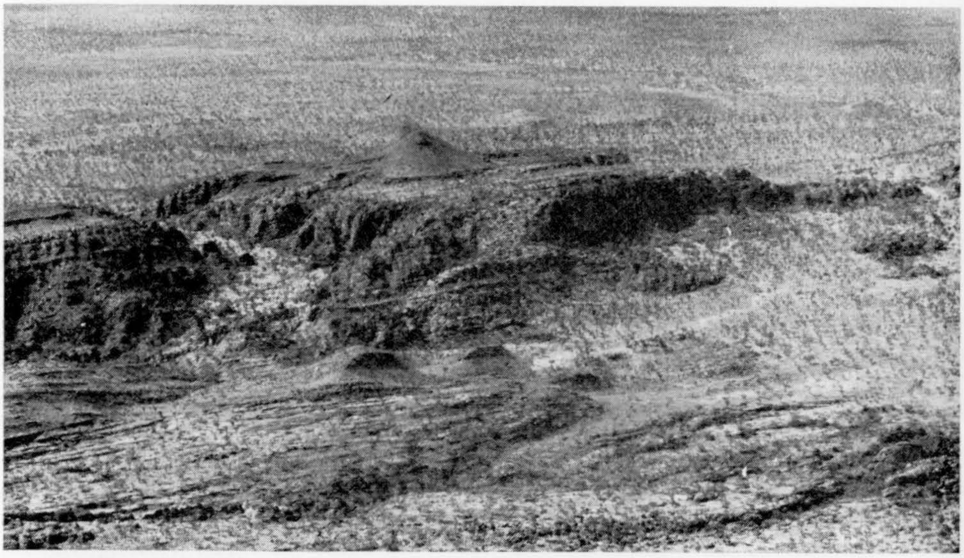


Plate 36, Figure 2. Aerial view, looking east, of the Pretlove Hills showing a small conical outlier of horizontal Point Spring sandstone(?) unconformably overlying dipping Cockatoo Formation

Plate 37, Figure 1. Loose broken block of quartzite of the Keep Inlet Beds at locality 23-1, 4 miles southwest of Cleanskin Bore

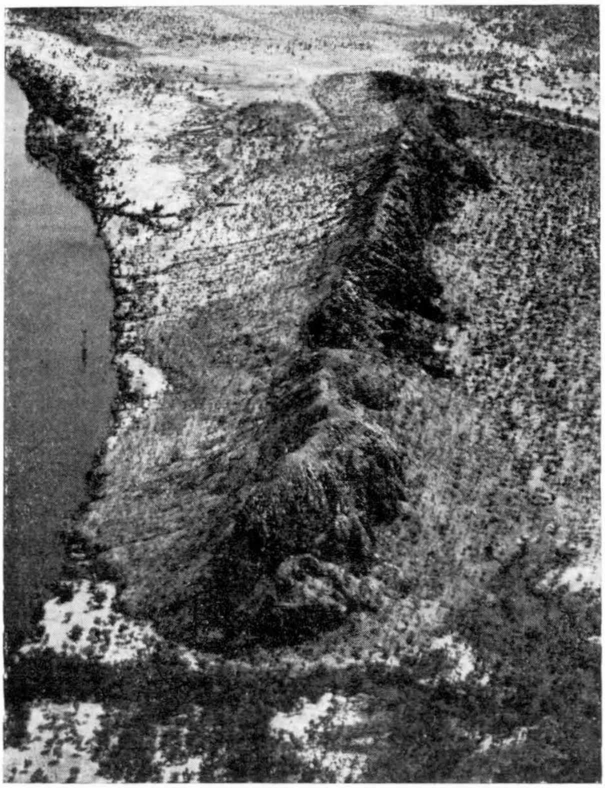


Plate 37, Figure 2. Looking north along crest of faulted Carlton Range. Kellys Knob Member on right, Antrim Plateau Volcanics on left of the crest, Ord River on left. Cf. fig. 10 of Matheson & Teichert (1958)

Plate 38, Figure 1. Knob Peak Bore. Looking north at spring at boundary between timbered sandy eluvium (foreground) and grassed plains behind the tidal mud flats (background). The bore is at the southeastern end of the pond. Photo taken September 1963. This and other springs in the area are known to dry at the end of some dry seasons

Plate 38, Figure 2. Looking southeast over the tidal flats on the eastern side of Keep Inlet. The main channel of Keep Inlet is in the background, and in the foreground are tidal channels bordered by mangroves

Geological History

The geological history of the Spirit Hill area is summarized in Figure 57. The figure shows the following events:

A. Deposition on the Precambrian basement of the Cockatoo Formation and Buttons Beds(?).

B. Erosion of part of the Buttons Beds(?) followed by the deposition of units 1 and 2 of the Burt Range Formation.

C. Gentle folding, erosion of unit 2 of the Burt Range Formation, especially from the eastern limb of the anticline, followed by the deposition of unit 3 of the Burt Range Formation.

D. Erosion of unit 3 of the Burt Range Formation followed by the deposition of a carbonate equivalent of the Enga Sandstone, and the Septimus Limestone.

E. Erosion of the Septimus Limestone and most of the Enga Sandstone equivalent followed by the deposition of the Milligans Beds.

F. Faulting, erosion of the Milligans Beds and deposition of the Border Creek Formation.

G. Major faulting (post-Upper Carboniferous) and erosion to the present day.

The breaks between or within the formations are shown in Figure 54. They were probably caused by gentle folding and possible minor faulting in the Spirit Hill area. Faulting is not shown below the middle to upper Visean because there is little evidence on which the faults could be based. Downfaulting was probably responsible for the preservation of the Septimus Limestone at locality 272, immediately east of Spirit Hill.

WEABER RANGE

Traves (1955, p. 78) defined the Point Spring Sandstone as the 'sandstone and other sediments which crop out in the Weaber Range'. Later work has shown that Traves' Point Spring Sandstone consists of three stratigraphical units which, in descending order, are: Border Creek Formation, Point Spring Sandstone, and Burvill Beds.

The Point Spring Sandstone rests conformably on the Burvill Beds, and both formations are disconformably overlain by the Border Creek Formation. Only the Point Spring Sandstone is completely exposed; the base of the Burvill Beds is covered, and the top of the Border Creek Formation is covered or eroded. The Burvill Beds are exposed in the scarp of the Weaber Range, which is a cuesta, and the Point Spring Sandstone and the Border Creek Formation are exposed in the dissected dip slope (Pl. 33, fig. 1). The Burvill Beds and Point Spring Sandstone are fossiliferous and their age is known. The Border Creek Formation contains only poorly preserved plants, and its age is known only by reference to superposition.

Burvill Beds (new name)

The Burvill Beds are here defined as the sequence of sandstone, shale, and interbedded sandy limestone that is conformably overlain by the Point Spring Sandstone or disconformably overlain by the Border Creek Formation in the Weaber Range. The interval 0 to 160 feet in section 453 (Fig. 59) at Point Burvill, 1 mile east of Ningbing homestead, is here designated as the type section.

Figure 59. Columnar sections of Weaber Range, Burvill Point, and Öpik Hill areas. (See Figs 60 and 33 for location. Section 457 is 6 miles southeast of Ningbing homestead)

The co-ordinates of its base are latitude 15°15½'S., longitude 128°41'E. The Burvill beds crop out discontinuously along the scarp of the Weaber Range from Utting Gap to the Northern Territory border (section 452). The only outcrops known outside the Weaber Range and environs are at Milligans Hills. The interval 0 to 280 feet in section 435 is the thickest measured section of the Burvill Beds.

The type section (interval 0-160 ft of section 453) consists mainly of coarse-grained ferruginous quartz sandstone with subordinate interbedded sandy limestone, which is locally ferruginized. Part, if not all, of the covered interval between 87 and 120 feet consists of shale, as indicated by patches of loamy soil. Pelecypods, brachiopods, gastropods, and trace fossils are common. The overlying Point Spring Sandstone or Border Creek Formation is locally ferruginized, and contains a bed of conglomeratic sandstone overlain by cross-bedded pebbly sandstone with trace fossils.

Sequences of the Burvill Beds like the type section are found in section 465, near Öpik Hill, which contains a ferruginous shale at its base, and in section 457, 5 miles southeast of Burvill Point. East of Point Spring, the coarse sandstone of the Burvill Beds is represented by poorly exposed calcareous shale which weathers khaki, and fine-grained calcareous sandstone, best seen at the base of section 458 (Fig. 60), 3½ miles east-northeast of Point Spring. The distinctive feature of the Burvill Beds, regardless of whether its dominant component is coarse sandstone or shale, is its sandy limestone. Grey where fresh and red-brown where ferruginized, this limestone contains abundant subrounded very coarse sand grains or granules of lustrous quartz which impart a distinctive texture to the rock. The matrix consists of finer angular quartz grains and broken fossils cemented by recrystallized, partly dolomitic, limestone.

Among the abundant fossils in the Burvill Beds, brachiopods and trace fossils are widespread; pelecypods are almost restricted to the coarse sandstone in the northwestern part of the outcrop. Conodonts were found in section 435.

The only outcrops of Burvill Beds found in front of the Weaber Range are at locality 5/2 (Fig. 31), 1 mile south of Ningbing homestead, and locality 306, half a mile east of Ningbing. Locality 5/2 is a low isolated outcrop, discovered by E. P. Utting (pers. comm.), of very coarse calcareous sandstone which contains abundant rugose corals and polyzoans as well as brachiopods. At locality 305, 1½ miles northeast of Ningbing, a similar outcrop with the same fossils is overlain by Point Spring Sandstone. At locality 306, half a mile east of Ningbing homestead, ferruginized limestone with pelecypods and brachiopods, and sandstone apparently lie beneath section 453. As mentioned on page 58, locality 5/2 lies only a few hundred yards east of the eastern edge of the outcropping Ningbing Limestone, but erratic dips in this area obscure the relationships between the Burvill Beds and Ningbing Limestone. The correlation of the Burvill Beds with the basal pebbly sand of the Waggon Creek Breccia indicates that they are a basal transgressive deposit that unconformably overlies the Ningbing Limestone.

At Milligans Hills the Burvill Beds consist of brown coarse-grained gritty calcareous sandstone and sandy limestone (Fig. 52). Section 147, on the westernmost hill (Fig. 39), consists of 75 feet of fossiliferous calcareous sandstone and limestone overlain by sandstone and conglomerate of the Border Creek Formation. Section 148, on the easternmost hill, contains fine to medium-grained sandstone at the base, overlain by fossiliferous limestone and calcareous sandstone, which

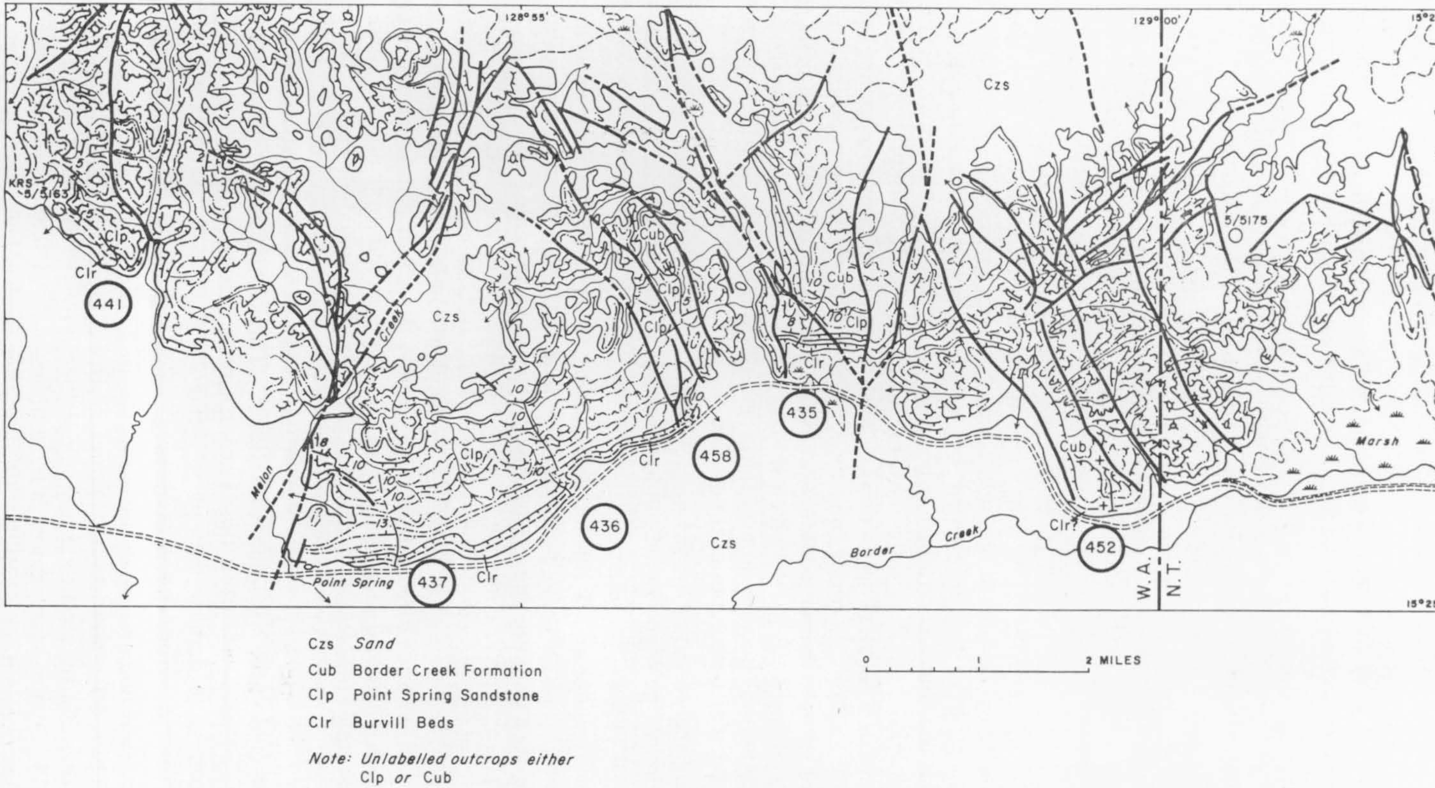


Figure 60. Geology of eastern part of Weaber Range. (Modified from photogeological map by R. Richard)

are succeeded by ferruginized limestone and sandstone. Section 148 appears to be continuous with that in Milligans No. 1 Bore, drilled only a quarter of a mile from the 148 section line.

Fauna and Age. The Burvill Beds contain a rich fauna of brachiopods and gastropods as well as ostracods and conodonts.

G. A. Thomas (1962, p. 731) listed a fauna from Point Spring and Milligans Hills and suggested that it was Visean to Namurian. When he wrote, the Burvill Beds were not separated from the Point Spring Sandstone, and the plants that he listed probably came from the Point Spring Sandstone (sensu stricto). The remainder of the fossils in his list from near Point Spring probably came from the rocks we now call Burvill Beds. The fossils from Milligans Hills are in the Burvill Beds.

Conodonts from the Weaber Range (section 435) indicate an age of not older than upper Visean ($CuIII_{\beta}$) and possibly as young as Namurian, and foraminifers (B. L. Mamet, pers. comm.) an age of upper Visean ($CuIII_{\beta\text{-}\gamma}$).

According to these determinations the Burvill Beds are equivalent to the lower part of the Tanmurra Formation in the Bonaparte No. 1 well (Fig. 40); as yet no correlation based on common species can be made between the two formations.

Point Spring Sandstone

Noakes et al. (1952, p. 101) introduced the name Point Spring Sandstone for the sandstone at Point Spring; they divided it into lower marine beds with brachiopods, overlain by upper lacustrine beds with plants, and regarded it as Permian. Traves (1955, pp. 78-9) defined the Point Spring Sandstone as the 'sandstone and other sediments which crop out in the Weaber Range'. He quoted description of two sections from an unpublished report by F. Reeves. We identify the interval 0 to 235 feet of Reeves' measured section east of Ningbing as Burvill Beds, and the overlying interval from 235 to 355 feet as Point Spring Sandstone. Reeves' other section, 4 miles northwest of the State boundary, corresponds with our section 435; the interval 0 to 250 feet in Reeves' section is identified as Burvill Beds, 250 to 400 feet as Point Spring Sandstone, and 400 to 450 feet (top of the section) as Border Creek Formation. Thomas (*in* Traves, 1955) was the first to point out that the Point Spring Sandstone is Carboniferous.

The Point Spring Sandstone is here redefined as the sheet of quartz sandstone that conformably overlies the Burvill Beds and is disconformably overlain by the Border Creek Formation in the Weaber Range. The interval 135 to 760 feet in section 458 (Fig. 59), 4 miles northeast of Point Spring (Fig. 60), is designated as the type section. The co-ordinates of the base of the type section are latitude 15°23½'S., longitude 128°56½'E. The interval 220 to 1,100 feet (890 ft) in section 436 is the thickest known occurrence of the Point Spring Sandstone.

The type section and other sections of the Point Spring Sandstone consist of an alternation of jointed cross-bedded medium to coarse yellow to white quartz sandstone and laminated to thin-bedded fine quartz sandstone with abundant trace fossils. In many parts of the Weaber Range, particularly in the type area, the jointed and cross-bedded sandstone, like similar sandstone in the Cockatoo Formation, is etched into characteristic castle-like outcrops which on the ground and on air-photographs are readily distinguished from the associated thin-bedded sandstone (Pl. 33, fig. 2). The regular alternation of these contrasting sandstones limits the scope of photogeological interpretation in the Weaber Range; where continuity of outcrop is broken by faults or by cover, as in the type area, the absence of reliable markers in the Point Spring Sandstone rules out positive identification. The best link between sections is the boundary between the Burvill Beds and the Point Spring Sandstone, and in many places this boundary is obscure on the air-photographs. Moreover, even in a small area, most beds are hard to trace because of rapid lateral change, as shown in sections 437, 436, and 458 (Fig. 59). Some beds can be traced between these sections, but many do not persist from one section to another.

The jointed and cross-bedded sandstone is coarse, with rare pebbles of quartz and quartzite. Like similar sandstone in the Cockatoo Formation, it is friable. The thin-bedded sandstone is firmer, and contains numerous silicified or ferruginized 'hard-grounds' (Voigt, 1959), which, because of their good exposure, are valuable local markers.

The Point Spring Sandstone abounds in minor sedimentary structures. Cross-bedding is common, as are ripple marks and contorted bedding. Trace fossils are abundant in the thin-bedded sandstone.

Brachiopods, pelecypods, and plants are most abundant near the base, but, as shown by the type section, extend almost to the top; so it is mostly, if not entirely, marine.

Fauna and Age. Two distinct brachiopod faunas have been collected: at the base of the formation the fauna is approximately the same as that in the underlying Burvill Beds and is thought to be uppermost Visean to lowermost Namurian in age; the upper fauna, from locality 458/12 at the top of the sandstone, is probably Namurian. These age determinations confirm those of Thomas (1962).

According to these determinations the Point Spring Sandstone is equivalent to the upper part of the Tanmurra Formation in Bonaparte No. 1 (Fig. 40); as yet no correlation based on common species can be made between the two formations.

Border Creek Formation

The Border Creek Formation, originally named by E. P. Utting in an unpublished report, is here defined as the sequence of quartz sandstone, pebbly quartz sandstone, conglomerate, and siltstone that disconformably overlies the Point Spring Sandstone and Burvill Beds in the Weaber Range. The top of the formation is eroded or covered. The interval 1,100 to 1,465 feet in section 436 (Fig. 59) is designated as the type section; it is the thickest measured section. The co-ordinates of the base of the section are latitude 15°23½'S., longitude 128°55'E. The Border Creek Formation in the Burt Range area has been described on pages 90-3, and the description here applies to the Weaber Range only.

The type section contains three beds of poorly exposed conglomerate with rounded pebbles and cobbles of vein quartz and quartzite (Pl. 34, fig. 1), and rare fragments of siltstone and sandstone. White or purple siltstone is a minor but distinctive part of the Border Creek Formation and forms an association with the conglomerate not found in the Lower Carboniferous sequence. In section 458, siltstone is the basal bed of the Border Creek Formation, and much of it was later eroded to form fragments up to 6 inches long in the overlying conglomerate and sandstone. The siltstone and siltstone breccia of the Border Creek Formation are its most distinctive components. The jointed and cross-bedded coarse quartz sandstone is indistinguishable from that of the Point Spring Sandstone.

Silicified fine white and purple silty sandstone contains *Phyllotheca*-like plants at 1,275 feet in section 436. This is the only fossil found in the Border Creek Formation in the Weaber Range.

The top of the Point Spring Sandstone is locally channelled to a depth of several feet and filled with the basal conglomerate of the Border Creek Formation (Pl. 34, fig. 2). Between section 436, which contains 890 feet of Point Spring Sandstone, and section 435, which contains 280 feet, the relief of the disconformity is 610 feet in a distance of 2½ miles. Details of a similar erosional surface of the Point Spring Sandstone between sections 400, 401, and 435 are shown in Figure 61. In the Öpik Hill area of the northwest Weaber Range, the entire Point Spring Sandstone is thought to have been eroded, and the Border Creek Formation overlies the Burvill Beds.

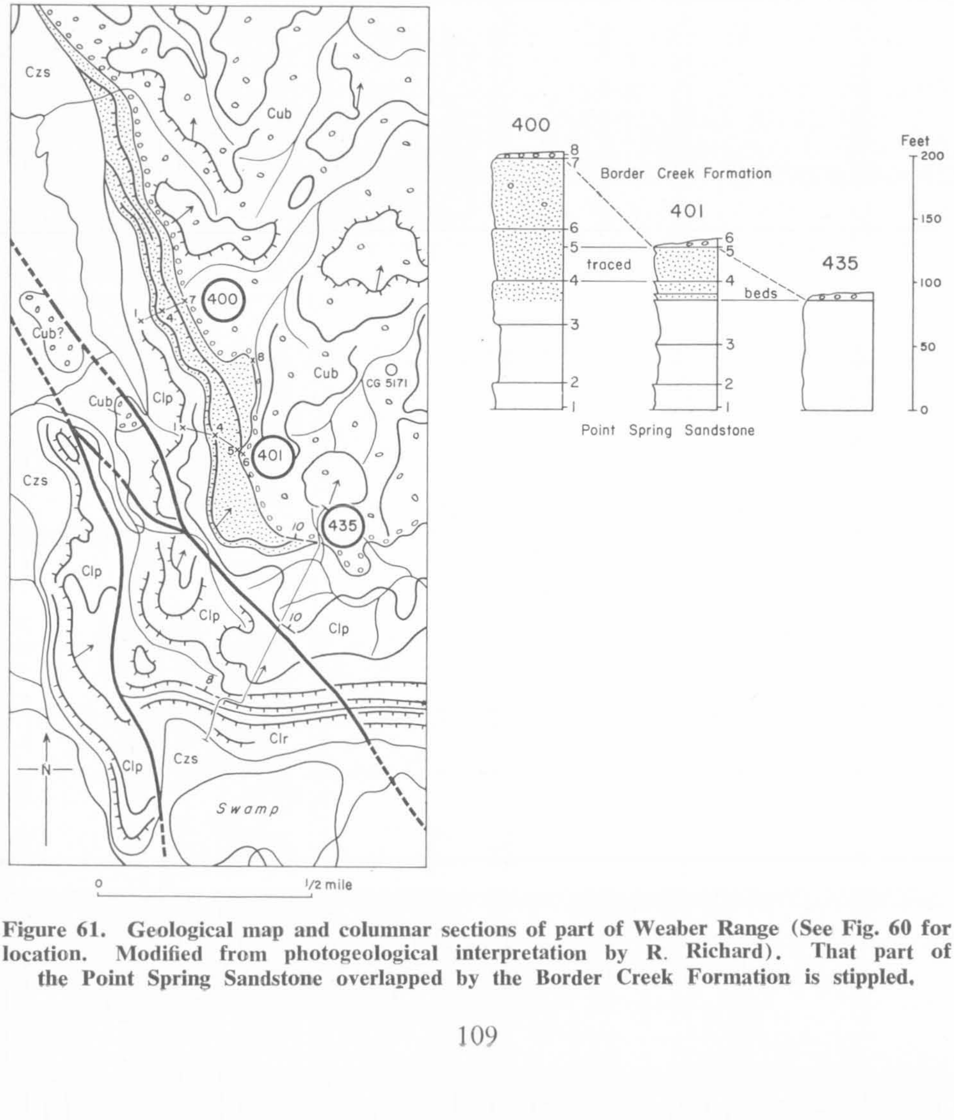


Figure 61. Geological map and columnar sections of part of Weaber Range (See Fig. 60 for location. Modified from photogeological interpretation by R. Richard). That part of the Point Spring Sandstone overlapped by the Border Creek Formation is stippled.

An isolated outcrop of claystone and conglomerate at locality 72, 9 miles south of Bonaparte No. 1 (Map 1), is identified as Border Creek Formation.

Age and Relationships. The only fossil known from the Border Creek Formation is a *Phyllotheca*-like plant which probably indicates a Carboniferous or Permian age. Because it disconformably overlies the Visean to early Namurian Point Spring Sandstone, the Formation is younger than early Visean; and because it is overlain by the Lower Permian Keep Inlet Beds, it is older than Permian; hence its age is Upper Carboniferous.

Occurrences of the Burvill Beds, Point Spring Sandstone, and Border Creek Formation Outside the Weaber Range

The Burvill Beds and the Point Spring Sandstone are distinctive units which can be readily identified in outcrops outside the Weaber Range. On the other hand, the Border Creek Formation, lying disconformably above older units and having its top eroded or covered, is less positively identified in other areas. All these occurrences are in the Burt Range Syncline, and are described on pages 90 and 101.

The offshore islets contain a sequence similar to that of the Border Creek Formation, but the two sequences may not be equivalent.

OFFSHORE ISLETS (Fig. 62)

Rocky Islet (lat. 14°43½'S., long. 128°38'E.) and Pelican Islet (lat. 14°46½'S., long. 128°47'E.) are situated in the southern part of Joseph Bonaparte Gulf 5 miles from the shore. As a guest of Anacapa Oil Exploration, Veevers accompanied Mr W. Jauncey on a brief visit by boat to the islets in July 1965.

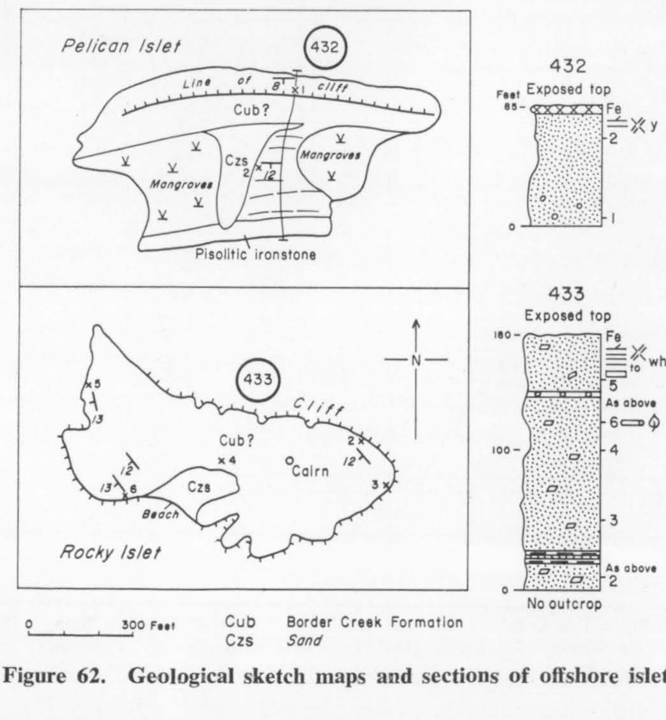


Figure 62. Geological sketch maps and sections of offshore islets

Rocky Islet (Pl. 35, fig. 1)

A southwesterly dipping sequence, roughly 180 feet thick, was measured across Rocky Islet. It consists mainly of cross-bedded silicified micaceous silty quartz sandstone which commonly contains fragments of white siliceous siltstone that range from a fraction of a millimetre to fragments of platy breccia occasionally up to 20 inches long (Pl. 36, fig. 1). Sandstone near the exposed base contains blocks of banded siltstone 3 feet long and 18 inches wide. White siltstone is interbedded with the sandstone 25 feet above the base. A thin bed of conglomerate, with pebbles of quartzite, crops out at 140 feet. *Phyllotheca*-like plants, probably indicating a Carboniferous or Permian age, were found at locality 433/6; this is the only fossil known from the islets.

Pelican Islet (Pl. 35, fig. 2)

A south-dipping sequence, roughly 85 feet thick, was measured across Pelican Islet; it consists of cross-bedded yellow micaceous silty quartz sandstone with pebble bands at the exposed base. The sequence, like that on Rocky Islet, is deeply weathered, and is capped by 5 feet of pisolitic ironstone.

The relationships of the sequences in Rocky and Pelican Islets to each other and to the rest of the Bonaparte Gulf Basin are unknown. Within the interval Carboniferous to Permian the islet sequences resemble parts of the Border Creek Formation and parts of the Permian sequence of the Port Keats area. The resemblance between the Rocky Islet sequence and the Border Creek Formation is strengthened by the occurrence in both of *Phyllotheca*-like plants. Further evidence provided by structure is discussed below.

NORTHWESTERN AREA

Outliers of Barren Sandstone in the Pretlove Hills and Ningbing Range

At locality 67/1, on the northeastern edge of the Pretlove Hills (Pl. 36, fig. 2; Map 1), 4 miles west of the Jeremiah Hills, 70 feet of horizontal barren medium-bedded buff silicified quartz sandstone unconformably overlies tilted quartz sandstone of the Cockatoo Formation. Conical outcrops of silicified sandstone at the foot of the northeastern part of the Pretlove Hills and an outcrop southeast of No. 8 Tank are probably the same unit.

An outcrop of white silicified sandstone that unconformably overlies the Ningbing Limestone at locality 17/3, south of Tanmurra Creek (Fig. 33), is also probably the same unit. This outcrop consists of tumbled blocks only, but it is probably unconformable as it occupies a depression in the underlying limestone.

All the outcrops are mapped tentatively as Point Spring Sandstone, but it is possible that they are a non-calcareous part of the Burvill Beds.

Utting Calcarenite (new name)

Utting Calcarenite is the name here given to the calcarenite cropping out at the head of the valley between the Ningbing Range and the northern extension of the Weaber Range (Fig. 63). It is also found at an isolated outcrop 5 miles to the south near Tanmurra Creek (Map 1). In the type area the formation is probably faulted against Devonian Ningbing Limestone; the lower part of the formation is exposed as isolated ribs of carbonate rock, and the upper part crops out as benches beneath the Burvill Beds and Point Spring Sandstone, and has a faintly layered pattern on the air-photographs.

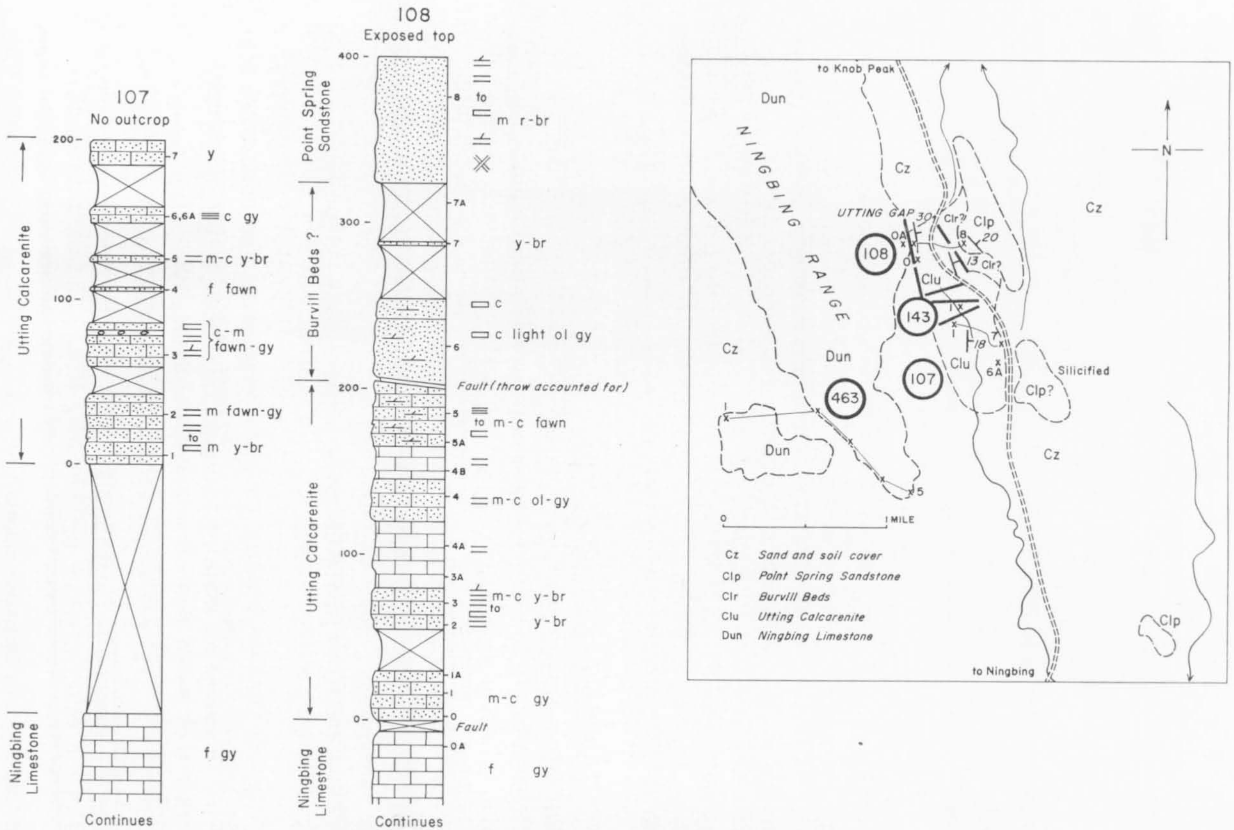


Figure 63. Geological map and columnar sections, Utting Gap

The formation is named after Utting Gap (Fig. 63), in the divide between the drainage running north into mud flats and that running into the tidal channels at the false mouths of the Ord River in Cambridge Gulf.

E. P. Utting (pers. comm.) was the first to examine the calcarenite and sent a collection of fossils for identification to G. A. Thomas. Thomas (1965b) reported that the fauna was younger than that in the Septimus Limestone, but older than that in the Point Spring Sandstone (the lower and most fossiliferous part of which is now called the Burvill Beds).

Type Section. The type section, section 108, is measured across Utting Gap from the edge of the Ningbing Limestone to the western scarp of a small butte (Fig. 63). The co-ordinates of the base of the section are latitude 14°58′S., longitude 128°56′E. The lowermost beds are thought to be faulted against the Ningbing Limestone because the contact between the formations is oblique to the strike and is slightly ferruginized; the dip of the calcarenite steepens towards the contact. Additional evidence to support faulting against the Ningbing Limestone is found south of the type section, where the beds near the Ningbing Range are drag-folded.

It is possible, however, that the relationship between the Utting Calcarenite and the Ningbing Limestone is an abutment unconformity (Fig. 64) and that the faulting is a later minor adjustment of a major fault along the eastern side of the Ningbing Range.

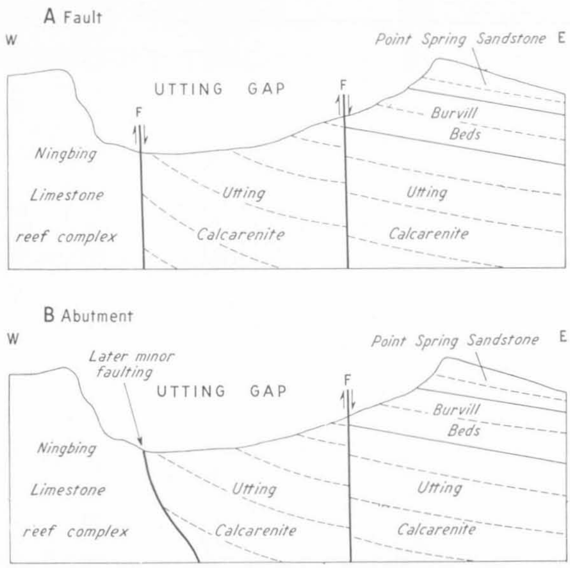


Figure 64. Possible relationship between Utting Calcarenite and Ningbing Limestone at Utting Gap: (A) faulted contact, (B) abutment unconformity

The Utting Calcarenite is a coarse to medium-grained grey, yellow-brown, and fawn skeletal sandy calcarenite. It is usually thin to medium-bedded, is sometimes cross-bedded or laminated, and contains abundant silicified fossils.

In section 108 the overlying Burvill Beds are faulted against the calcarenite, but to the southeast the contact seems to be conformable. The throw on the fault has been accounted for in the columnar section (Fig. 63).

Fossils indicate that the rocks in section 107, half a mile to the south, are slightly older than those in the type section. The two sections cannot be linked because of transverse faults and drag folds in the intervening area. The rocks in section 107 are thin-bedded yellow, brown, or grey sandy calcarenite, and crop out as isolated ribs; between the ribs are probably softer beds of shaly calcarenite.

The thickness of the type section is 200 feet, and the formation is estimated to be more than 400 feet thick.

Fauna and Age

The Utting Calcarenite contains a rich fauna of brachiopods, tabulate and rugose corals, the latter up to 3 inches across and 9 inches long, trilobites, foraminifers, ostracods, conodonts, and sharks. The sharks have been identified by Joyce G. Tomlinson (BMR, pers. comm.) as *Psammodus* sp. and *?Ctenacanthus* sp.

Thomas (1965b) described a new species, *Delepinea uttingi,* from the Utting Calcarenite and concluded that it was closest to species from the early Visean in Belgium, Britain, and Ireland. He regarded the other brachiopods associated with *D. uttingi* as also indicative of the early Visean. Conodonts confirm this age and are the same as those in the $CuII_{\delta}$ to $CuIII_{\alpha}$ Zones of Germany (Jones & Druce, 1966; Druce, 1968). The foraminifers and ostracods indicate a correlation between the Utting Calcarenite and shale (Bonaparte Beds) between cores 6 and 8 in Bonaparte No. 1.

Waggon Creek Area

Unnamed Breccia

An unnamed mid-Tournaisian breccia on the southern side of the Waggon Creek valley (Veevers & Roberts, 1966) rests with angular unconformity on sandstone and dolomite of the Frasnian Cockatoo Formation. It is overlain, presumably unconformably, by sandstone tentatively identified as the Visean to Namurian Point Spring Sandstone.

The breccia consists of about 100 feet of dolomite breccia containing a bed of marly dolomite. The dolomite fragments in the breccia are up to 3 feet long and are believed to have been derived mainly from dolomite in the underlying Cockatoo Formation.

Brachiopods and conodonts in the matrix of the breccia indicate a correlation with the uppermost beds of the Burt Range Formation or the lowermost beds of the Enga Sandstone, which are equivalent to the middle part of the $CuII_{\alpha}$ Zone of Germany, or the upper part of the K Zone of Britain.

The breccia is probably the only preserved shoreline deposit of the Tournaisian in the Bonaparte Gulf Basin, and was deposited during the transgression of the sea into the Waggon Creek Valley after the faulting, tilting, uplift, and erosion of the greater part of the northwestern platform province. We argue that these movements took place after the deposition of the Tournaisian reef limestone at Ningbing because faulting, uplift, and erosion of such magnitude would have disrupted the growth of the reef. If so, the northwestern part of the platform was faulted, tilted, and uplifted during part of the Tournaisian (middle part of the K Zone of Britain, i.e. upper Burt Range time). The southeastern part of the platform was unaffected by these movements, and deposition continued.

Waggon Creek Breccia

The Waggon Creek Breccia (Veevers & Roberts, 1966), an equivalent of the Burvill Beds, was deposited at the foot of cliffs surrounding the ancient Waggon Creek valley during the later upper Visean transgression. The breccia lies with angular unconformity on the Cockatoo Formation and is overlain, apparently conformably, by sandstone identified as Point Spring Sandstone.

The breccia comprises a friable basal pebbly sandstone, about 20 feet thick, which appears to have been cemented originally with calcium carbonate, and an overlying breccia, about 165 feet thick, containing tabular blocks of dolomite up to 30 feet across and subangular to rounded fragments of metaquartzite and vein quartz up to 1 foot across, set in a dark sandy dolomitic matrix. Channels in the top of the pebbly sandstone are infilled with breccia, and the sandstone is considered to have been consolidated into beach rock before the overlying breccia was deposited. The breccia is interpreted as a deposit which accumulated at the foot of dolomite cliffs. The sandstone interbedded with the dolomite in the Cockatoo Formation was rapidly removed by the sea, and the dolomite collapsed in a mass of angular blocks. Coarse sand and boulders from onshore gravels were washed between the blocks of dolomite and were later cemented by carbonate minerals.

Brachiopods and pelecypods from the basal pebbly sandstone are the same as those in the Burvill Beds, and hence are dated as late Visean to possibly early Namurian.

Basinal Area

Bonaparte Beds (new name)

The Bonaparte Beds are here defined as the thick sequence of dark shale, siltstone, and sandstone beneath the Tanmurra Formation in the interval 1,630 to 10,530 feet (total depth) in the Alliance Oil Development Bonaparte No. 1 well at latitude 15°01′S., longitude 128°44′40″E., 16 miles east-northeast of Ningbing station. The beds are also known from beneath the Tanmurra Formation in Bonaparte No. 2, 5 miles south-southwest of Bonaparte No. 1, and in the Kulshill Nos 1 and 2 wells near Port Keats.

The Bonaparte Beds are named after the Bonaparte No. 1 well. They constitute a basinal facies in the central part of the Bonaparte Gulf Basin and, because they extend from the Upper Devonian into the Lower Carboniferous, are laterally equivalent to most of the sandstone and limestone deposited on the platform.

Succession in Bonaparte Nos 1 and 2 Wells

The succession in Bonaparte No. 1 and No. 2 has been described by Le Blanc (1964, unpubl., 1965, unpubl.), and the lithological details in the graphic logs (Fig. 65) are derived from his reports.

Type Section. The Bonaparte Beds consist of varying proportions of shale, siltstone, sandstone, and carbonate rock. Le Blanc (1964) distinguished the following lithological units in Bonaparte No. 1:

Depth (ft)	
1,630-3,800	Shale with rare siltstone interbeds
3,800-6,453	Shale with some interbedded porous sandstone
6,453-7,100	Silty shale with common interbedded siliceous sandstone
7,100-7,480	Shale
7,480-7,865	Shale

7,865-8,195	Shale and siltstone	
8,195-8,300	Sandstone	
8,300-9,035	Shale and siltstone	
9,035-9,260	Sandstone	
9,260-9,492	Variegated shale	
9,492-10,530	(T.D.)	Sandstone, siltstone, shale

The sandstone is siliceous and silty; most of the shale is variegated; the siltstone is slightly calcareous and commonly siliceous. In the interval 10,280 to 10,320 feet, the siltstone grades into silty microcrystalline limestone.

The colour of most of the shale in the Bonaparte Beds ranges from medium dark grey(N4) to dark grey(N3), as defined in the Rock Chart of the Geological Society of America. According to Dr F. C. Loughnan (pers. comm.), the dark pigment is organic carbon, which constitutes about 1 percent by weight of the shale. The variegated shale near the bottom of Bonaparte No. 1 is mainly green, with minor black, brown, and rust. The shale of many cores has flowed plastically, probably before it was consolidated, and is commonly slickensided. Lenticles of sandstone and siltstone are widespread in the shale.

Dr F. C. Loughnan's (pers. comm.) mineralogical analysis of cores from Bonaparte No. 1 shows breaks between the Tanmurra Formation and top of the Bonaparte Beds (between cores 5 & 6), and between cores 26 and 27. From core 27 downward, the Bonaparte Beds contain more quartz (40% or more) and small amounts of chlorite, calcite, and dolomite, which are not found above. Among the clay minerals in the Bonaparte Beds, mixed-layer minerals predominate and, except for a few cores with 20 to 25 percent kaolinite, this mineralogy 'is in accordance with a marine origin'.

The interval between cores 26 and 27, marked by a mineralogical break, is further marked by a structural break detected by a dipmeter survey. Above 7,472 feet, the dip is northerly, whereas from 7,520 to 8,524 feet it is east-southeasterly, and from 8,524 to 9,949 feet (the greatest depth surveyed) it is southerly or southeasterly. From cores, the amount of dip is known to be generally 2° to 3° from the top to 7,480 feet, and 4° to 6° from 7,480 feet to the bottom. Le Blanc interprets this information as an angular unconformity in the interval 7,472 to 7,520 feet.

In Bonaparte No. 2, Le Blanc distinguished the following units:

Depth (ft)	
1,577-3,274	Shale with rare interbeds of siltstone
3,274-4,541	Silty shale with common interbedded sandstone, including pebbly sandstone from 3,562 feet to 3,568 feet
4,541-4,950	Shale with several beds of sandstone
4,950-5,548	Shale
5,548-6,675	Silty to sandy shale with interbedded sandstone
6,675-7,008 (T.D.)	Shale and sandstone

A zone of faulting was found between 4,950 and 5,100 feet. The dip from 5,100 feet to total depth is southeasterly at 3° to 4°.

Fauna and Age. D. J. Belford, P. J. Jones, and J. Roberts (BMR) have identified the fauna, mainly from cores, in both the Bonaparte wells (Appendixes *in* Le Blanc, 1964, unpubl.; 1965, unpubl.).

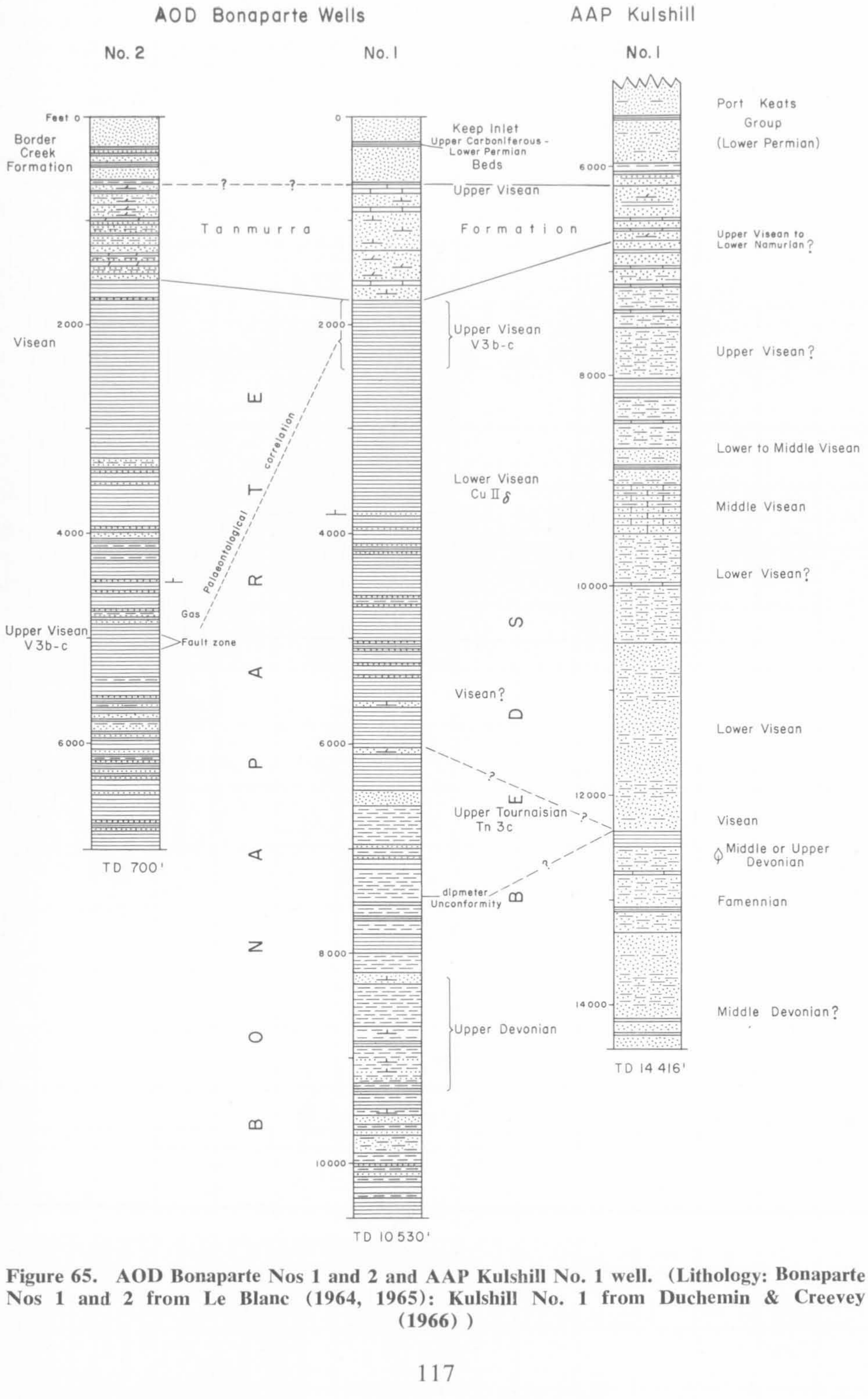


Figure 65. AOD Bonaparte Nos 1 and 2 and AAP Kulshill No. 1 well. (Lithology: Bonaparte Nos 1 and 2 from Le Blanc (1964, 1965): Kulshill No. 1 from Duchemin & Creevey (1966))

Richly fossiliferous beds in the upper part of the Bonaparte Beds in Bonaparte No. 1 contain foraminifers, ostracods, brachiopods, pelecypods, and conodonts. Fossils are less common lower in the sequence and many of the rocks are barren or contain only fragmentary fossils. The sandstone at the bottom of the well is barren.

The fossils show that the Bonaparte Beds are almost entirely marine. Though conchostracans, found in core 29 (8,856 ft) in Bonaparte No. 1, typically indicate a brackish environment, they are associated with pelecypods and trilobites and are thought to have been washed into marine sediments.

The sequence in Bonaparte No. 2 contains very few fossils; all that have been found are fragmentary conodonts in cores 3 and 5, immature ostracods in core 7, and foraminifers, brachiopods, and conodonts in core 11 at 4,920 feet.

Le Blanc (1964) reports a dipmeter unconformity between 7,472 and 7,520 feet in Bonaparte No. 1 which may represent a break between the Devonian and Carboniferous. The rocks on either side of the unconformity are barren and it cannot be dated precisely. The nearest dated rocks are Upper Devonian beds in core 28 (8,310 ft) and Lower Carboniferous beds in core 24 (6,610 ft), so that there may well be a conformable Devonian/Carboniferous sequence in the interval.

The Bonaparte Beds in Bonaparte No. 1 are dated as follows: cores 6 to 8 (1,840-2,410 feet), Visean(V3b-c) from foraminifers; core 12 (3,500 ft), lower Visean ($CuII_{\delta}$) from conodonts; core 24 (6,610 ft), upper Tournaisian (Tn3c) from foraminifers; and core 28 (8,310 ft), Upper Devonian from pelecypods.

In Bonaparte No. 2, conodonts in core 3 (2,170 ft) suggest a Visean age, and foraminifers date core 11 (4,920 ft) as Visean(V3b-c).

Correlation. The upper Visean foraminifers and ostracods show that the interval between cores 6 and 8 (1,840-2,410 ft) in Bonaparte No. 1 is equivalent to core 11 (4,920 ft) in Bonaparte No. 2.* This probably means that, if the rate of deposition was uniform, there is about 2,600 feet of shale immediately beneath the Tanmurra Formation in Bonaparte No. 2 which is not represented in Bonaparte No. 1 because of an unconformity beneath the Tanmurra Formation. Alternatively, the extra section could have been deposited more rapidly contemporaneously with the shale above core 6 in Bonaparte No. 1; or, as discussed on page 120, it could be laterally equivalent to the Tanmurra Formation in Bonaparte No. 1 (in which case the rocks between 608 and 1,577 ft, which are described as Tanmurra Formation by Le Blanc, 1965, unpubl., in Bonaparte No. 2 would be younger than the Tanmurra Formation).

The Visean Utting Calcarenite is equivalent to shale between cores 6 and 8 in Bonaparte No. 1 (Fig. 40).

The Visean foraminiferal fauna from core 9 of Bonaparte No. 1 has been recognized in the upper parts of the Milligans Beds in Milligans No. 2 Bore at Milligans Hills.

The Bonaparte Beds contain sediments equivalent to most of the Famennian to upper Visean parts of the outcropping succession, which includes the Ningbing

* Dr G. Playford (pers. comm.) has found closely similar spore assemblages in core 11 of Bonaparte No. 1 and core 3 of Bonaparte No. 2; the implied correlation conflicts with that based on foraminifers and ostracods.

Limestone, Buttons Beds, Burt Range Formation, Enga Sandstone, Septimus Limestone, and Zimmermann Sandstone (Fig. 40). Whether the Bonaparte Beds in the Bonaparte wells are complete or contain numerous hiatuses cannot be determined because of the limited palaeontological data available.

Succession in Kulshill Nos 1 and 2 Wells

The descriptions of the sections in Kulshill Nos 1 and 2 are summarized from Duchemin & Creevey (1966, unpubl.) and Creevey (1966, unpubl.).

In Kulshill No. 1 (Duchemin & Creevey, 1966), the Bonaparte Beds occupy the interval 6,707 to 14,416 feet (T.D.), and lie beneath the Tanmurra Formation. The Devonian part of this section (12,340-14,416 ft) has been described on pages 64-65. The Lower Carboniferous part of the Bonaparte Beds is entirely Visean; the Tournaisian is absent. Duchemin & Creevey have divided the Lower Carboniferous section as follows:

Depth (ft)	
6,707-7,535	Dark grey shaly siltstone, light grey sandstone with black to grey shale interbeds, and scattered light grey to brown limestone bands
7,535-8,695	Grey to dark grey shaly siltstone with black to dark grey shale; thin interbeds of light grey to white sandstone and dark grey limestone
8,695-10,550	Grey limestone, overlying grey to grey-green limestone, in turn overlying dark grey to black siltstone and shale
10,550-12,340	White to grey silicified sandstone, with interbedded dark grey to black shale and siltstone.

Marine fossils (mainly foraminifers) occur throughout, and indicate a Visean age. Brachiopods in core 27 also indicate a Visean age, probably uppermost Visean.

In Kulshill No. 2 (Creevey, 1966), the Bonaparte Beds occupy the interval 5,550 to 6,432 feet (T.D.), and consist of an upper sandstone and shale, middle shale and siltstone, and lower calcareous sandstone. Thin carbonate rocks are found in the upper and middle parts. Creevey (1966) has identified this section with the interval 6,707 to 7,535 feet in Kulshill No. 1.

Tanmurra Formation

The Tanmurra Formation is the name given by Le Blanc (1964, unpubl.) to the carbonate rocks and sandstone between 638 and 1,630 feet in the Bonaparte No. 1 well, which was drilled by Alliance Oil Development Australia N.L. 16 miles east-northeast of Ningbing station. He defined the formation as follows:

'The formation consists of an upper carbonate unit (86 feet), a medial sandstone unit (841 feet), and a basal carbonate unit (65 feet). The upper carbonate unit is buff to medium grey, sandy and silty, medium grained oolite which grades downwards to very sandy, slightly oolitic, coarse grained calcirudite, thence to a slightly arenaceous, very fine grained to fine grained calcarenite.

'The medial sandstone unit consists predominantly of white to medium grey, very fine grained to medium grained, angular, quartz sandstone with good intergranular porosity. The sandstones which are calcareous in the upper part of the unit, become dolomitic towards the base. Interbeds of micro-crystalline and very finely crystalline silty and sandy limestone and of recrystallised calcarenite are common

near the top of the unit. In the lower part of the unit interbeds of dolomite, consisting of altered crinoidal, bioclastic and fragmental carbonates, are common and locally the sandstone may contain as much as 40 percent of dolomitic carbonate matrix. Medium grey, calcareous siltstone is present between 830 feet to 860 feet and as thin interbeds elsewhere in the unit.
'The lower carbonate unit is a light brown, very fine grained to fine grained sandy calcarenite, which is in part pelletoidal.'

There is a gradational contact with the underlying Bonaparte Beds, and the base of the lower carbonate rock is chosen as the base of the formation (Fig. 65). Dr F. C. Loughnan (pers. comm.) has noted a distinct mineralogical break at this boundary.

The Tanmurra Formation is unconformably overlain by 622 feet of medium to coarse-grained sandstone identified as Keep Inlet Beds because a silty shale between 250 and 295 feet contains Upper Carboniferous to Lower Permian spores (P. R. Evans, BMR, pers. comm.), and a sandstone between 295 and 390 feet contains up to 20 percent of coloured mineral grains and lithic fragments.

In Bonaparte No. 2, 5 miles south-southwest of Bonaparte No. 1, a sequence of sandstone, dolomite, siltstone, and shale between 608 and 1,577 feet is identified as Tanmurra Formation (Le Blanc, 1965, unpubl.). The section is dominantly calcareous sandstone with thin interbeds of shale, siltstone, and dolomite; it contains less carbonate rocks than the type section (Fig. 65).

Le Blanc noted the abrupt contact with the underlying Bonaparte Beds in contrast to the gradational contact in Bonaparte No. 1, and thought that it might indicate an unconformity. Palaeontological evidence, on the other hand, indicates that the unconformity is more likely to be between the Tanmurra Formation and the Bonaparte Beds in Bonaparte No. 1. Foraminifers in core 11 at 4,920 feet in Bonaparte No. 2 are the same as those in the interval between cores 6 and 8 (1,840-2,410 ft) in Bonaparte No. 1, which means that there is about 3,350 feet of shale immediately beneath the Tanmurra Formation in Bonaparte No. 2 which is not represented in Bonaparte No. 1, assuming that the beds between 608 and 1,577 feet in Bonaparte No. 2 are Tanmurra Formation: there are no fossils in these beds to correlate them with the Tanmurra Formation in Bonaparte No. 1 and, as noted above, the sequence is not entirely lithologically similar to that in the type section 5 miles away. The following possibilities must be considered: (a) that the Tanmurra Formation in Bonaparte No. 1 is equivalent to the shale above core 11 in Bonaparte No. 2; (b) that the rocks between 608 and 1,577 feet in Bonaparte No. 2 are younger than the Tanmurra Formation and are not represented in Bonaparte No. 1 because of the hiatus between the Keep Inlet Beds and Tanmurra Formation; and (c) that downfaulting in the upper Visean around Bonaparte No. 2 resulted in the accumulation, in a graben, of a thick sequence of shale equivalent to that above core 6 in Bonaparte No. 1. In all cases it would not be necessary to postulate an unconformity between the Tanmurra Formation and the Bonaparte Beds in Bonaparte No. 1. Until these questions are resolved we intend to follow Le Blanc and identify the sequence in Bonaparte No. 2 as Tanmurra Formation.

The Tanmurra Formation in Bonaparte No. 2 is unconformably overlain by pure quartz sandstone, with minor interbeds of shale, identified as Border Creek Formation. The sandstone is lithologically distinct from the lithic quartz sandstone, identified as Keep Inlet Beds, at the top of Bonaparte No. 1, and is only 1 mile from outcrops of Border Creek Formation.

Duchemin & Creevey (1966, unpubl.) and Creevey (1966, unpubl.) have identified the Tanmurra Formation in the Kulshill Nos 1 and 2 wells, near Port Keats. In Kulshill No. 1 the formation is recognized between 6,175 and 6,707 feet, and consists of fine-grained white to light grey sandstone, and minor shale, dolomite, and limestone (Duchemin & Creevey, 1966, unpubl.).

In Kulshill No. 2, the Tanmurra Formation is recognized between 5,155 and 5,550 feet, and consists of white to light grey sandstone and minor shale, siltstone, and limestone (Creevey, 1966, unpubl.).

In both wells the Tanmurra Formation is overlain, probably unconformably, by an unnamed unit consisting of dark shale, limestone, and light grey sandstone. This unit contains a Lower Carboniferous microfauna, and a mixture of typical Lower Carboniferous and exclusively Permian spores, and possibly Upper Carboniferous spores also (Duchemin & Creevey, 1966, unpubl.; Creevey, 1966, unpubl.). The unnamed unit is considered to represent a Lower Permian reworking of Lower Carboniferous and possibly Upper Carboniferous sediments.

Age. The Tanmurra Formation is dated from foraminifers as upper Visean to possibly lowermost Namurian. Foraminifers from 650 to 670 feet in Bonaparte No. 1 indicate correlation with the upper part of the Belgian V3c Zone ($CuIII_{\delta}$ of Germany) or possibly with the lowermost Namurian; and from 679 to 687 feet indicate correlation with the $CuIII_{\beta}$ Zone of Germany (B. L. Mamet, pers. comm.).

In Kulshill No. 1, brachiopods from core 23 (6,697-6,718 ft), identified by Roberts, suggest an upper Visean to Namurian age. The same age is indicated by ostracods from a depth of 6,430 feet (Caye & Le Fevre *in* Duchemin & Creevey, 1966, unpubl.).

Stratigraphic Relationships. Figure 40 shows the Tanmurra Formation to be equivalent to the Burvill Beds and most of the Point Spring Sandstone. This relationship has been determined from the relative positions of sections, following the correlation of the Visean fauna in the Utting Calcarenite with that in cores 6 to 8 of Bonaparte No. 1, and the fauna in core 9 of Bonaparte No. 1 with that in Milligans No. 2 Bore, because, as yet, we cannot use fossils to correlate between the type sections of the Tanmurra Formation and the Burvill Beds and Point Spring Sandstone.

Environment of Deposition of the Basinal Facies

Marine fossils, chiefly brachiopods, foraminifers, and the pelecypod *Buchiola,* indicate that at least parts of the Bonaparte Beds and Tanmurra Formation are marine. The Upper Devonian part of the Bonaparte Beds lies on the seaward side of an equivalent carbonate reef complex, and is hence inferred to have been deposited in a slightly deeper part of the marine platform on which the reef complex was deposited. Associated with the indisputably marine fossils in the Upper Devonian are conchostracans, which are regarded as having lived in brackish water; the conchostracans were probably washed into the sea from the margin of the basin. The Tanmurra Formation and the Lower Carboniferous part of the Bonaparte Beds are likewise equivalent to a sequence of mainly shallow-water marine limestone and quartz sandstone, which were deposited near the margin of the basin. We therefore regard the Bonaparte Beds and Tanmurra Formation as deposits of the deeper offshore part of a marine shelf or platform, and this interpretation is shown in Figures 72 and 73.

An apparent conflict with this view stems from Dr G. Playford's study of the spores. In the Tanmurra Formation and in the Lower Carboniferous part of the Bonaparte Beds, Playford (pers. comm.) has found microfloral assemblages containing well preserved and morphologically diverse spores which have a considerable range in size (25-180 microns). These assemblages seem to represent a diverse land flora, and hence indicate close proximity of the depositional area to the land. In fact, the assemblages are strongly reminiscent of those from typical continental deposits of this age. Moreover, acritarchs, which are thought to indicate a marine depositional environment, are notably rare. In the earliest Lower Carboniferous and in the Upper Devonian sections, the spores are generally poorly preserved.

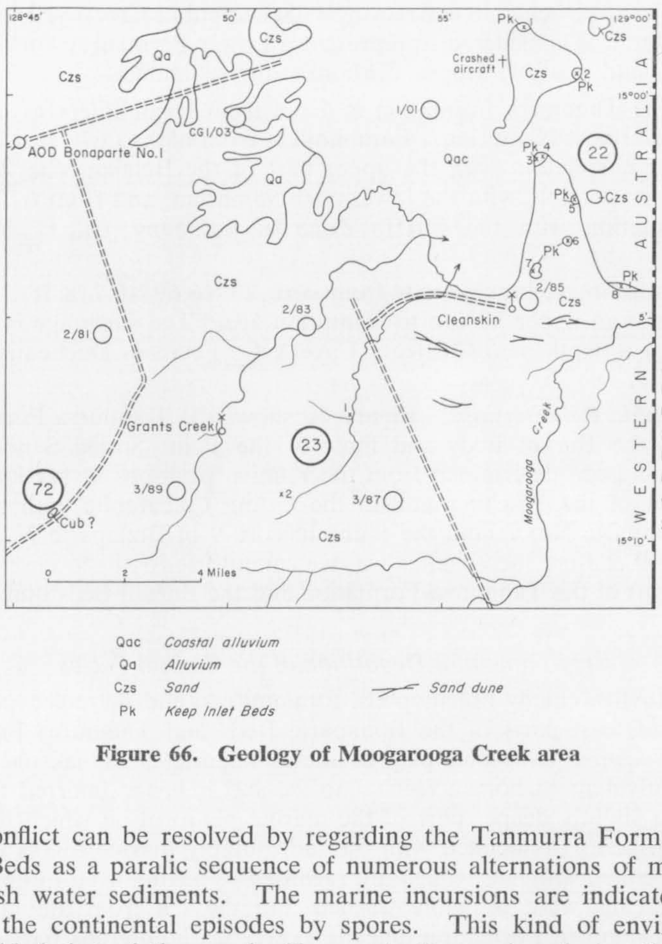


Figure 66. Geology of Moogarooga Creek area

This conflict can be resolved by regarding the Tanmurra Formation and the Bonaparte Beds as a paralic sequence of numerous alternations of marine, brackish, and fresh water sediments. The marine incursions are indicated by marine fossils, and the continental episodes by spores. This kind of environment probably resembled that of the nearby Bonaparte Depression during the Quaternary (van Andel & Veevers, 1967).

Figures 72 and 73 accommodate this interpretation if it is understood that the portrayed shorelines simply indicate the greatest extent of the sea, whose level frequently oscillated.

POST-CARBONIFEROUS

Keep Inlet Beds

Glover et al. (1955, unpubl.) proposed the name Keep Inlet Beds for the Permian glacial sediments in the Keep Inlet area. Outcrop in this area (Fig. 66) is extremely poor; the Keep Inlet Beds are the only consolidated rocks cropping out and the contacts with other Palaeozoic units are not exposed.

All the known outcrops of the Keep Inlet Beds lie north of Cleanskin Bore at or slightly above the level of the highest tides, which once or twice a year bring the sea across the broad salt-encrusted mud flats to the edge of the sand plain of the Moogarooga Creek area. Calcareous, feldspathic, and lithic quartz sandstone, locally pebbly, is the commonest rock in situ, and is found at localities 22/1, 3, 4, and 6. At locality 22/6, which is here designated as the type (co-ordinates lat. 15°03′S., long. 128°58′E.), the calcareous sandstone is lustre-mottled, and contains pellets of green mud in which Glover et al. (1955, unpubl.) found a brachiopod; the brachiopod has been determined by Professor Dorothy Hill as an immature *Strophalosia,* which indicates a Permo-Carboniferous, and probably Lower Permian, age. A subsequent search for fossils at this spot yielded only a reworked Ordovician conodont (P. J. Jones, BMR, pers. comm.). Rare glauconite was found in samples from localities 22/3 and 22/6.

The other chief component of the Keep Inlet Beds is a heterogeneous mixture of rock fragments, ranging from pebbles to blocks 3 feet across, which are best seen at locality 22/8. Pink orthoquartzite is the commonest type of fragment. Mr I. Gemuts (formerly of the Geological Survey of Western Australia) briefly examined our collection of fragments, and identified several types of granite, granodiorite, porphyry, schist, and subgreywacke, all of which are common in the Precambrian successions of the Kimberleys. Glover et al. (1955, unpubl.) also recorded a massive light grey quartzite, a boulder of which contains a poorly preserved indeterminate plant stem 8 inches long and 1 inch wide, and a Cambrian glauconitic limestone with *Biconulites*. The relationships between these fragments and the calcareous sandstone are not clear, but an outcrop of pebbly fontainebleau sandstone at locality 22/8, near the occurrence of numerous blocks, probably indicates that the calcareous sandstone enclosed the fragments. Glover et al. (1955, unpubl.) surmised that because of the large size of the biggest blocks and because of their heterogeneous lithology, age, and size, the rock fragments are glacial erratics, and we have no cause to question this.

Two large loose blocks of quartzite were found in the area to the south: one (Pl. 37, fig. 1), a cross-bedded quartzite measuring 6 by 4 by 3 feet, at locality 23/1, 5 miles southwest of Cleanskin Bore (Fig. 66); and the other at locality 23/2, 2 miles farther southwest. The blocks were found in sandy alluvium strewn with rounded cobbles and boulders of quartzite. No other type of rock was found. If, as their size suggests, the blocks belong to the Keep Inlet Beds, their association with quartzite gravel, devoid of other rock types found in the Keep Inlet Beds, is puzzling. The quartzite gravels are closely related to the conglomerate of the Border Creek Formation, and Dr G. A. Thomas (pers. comm.) has suggested that as the land surface was lowered by erosion the resistant blocks slowly dropped down into the eluvium of the Border Creek Formation. Alternatively, the quartzite gravel may have been derived from a quartzite-rich zone in the Keep Inlet Beds from which the chemically unstable rock fragments have been lost. Whichever explanation is accepted, it is concluded that the Permian Keep Inlet Beds overlie the Border Creek Formation of the Weaber Range, and thus mark the upper age limit of the Border Creek Formation.

A sequence of blue-grey and red claystone, overlain by a conglomerate composed of quartzite cobbles set in a matrix of sand, is exposed in a road cutting at locality 72, 9 miles south of Bonaparte No. 1 (Map 1); the beds are identified as Border Creek Formation.

The interval 60 to 638 feet in Bonaparte No. 1 (Le Blanc, 1964) (Fig. 65) consists of coarse-grained quartz sand and sandstone except for micaceous silty shale from 250 to 295 feet. P. R. Evans (BMR, pers. comm.) found Lower Permian spores in this shale. Between 295 and 390 feet, the poorly cemented sandstone contains '20 percent of coloured quartz grains and lithic fragments'. We identify the interval 60 to 638 feet as Keep Inlet Beds on the basis of the Lower Permian age of the shale, and the lithology of lithic sandstone. The kaolinitic sandstone below 390 feet may be interpreted as Border Creek Formation or Point Spring Sandstone.

STRUCTURE

Noakes et al. (1952) pointed out that 'the Bonaparte Gulf Basin as a structural unit probably extends north-westerly from the present coast line to the edge of the continental shelf', and this has been confirmed by recent surveys (Jacquemin, 1966; Veevers & van Andel, 1967; Veevers, 1967a and b). Noakes et al. pointed out that the Bonaparte Gulf Basin is roughly comparable in size to the Canning Basin, though it is largely submerged. The present report is limited to the southern landward part of the Bonaparte Gulf Basin and its outliers (Fig. 1), which is only a small, but not insignificant, part of the original depositional basin.

The original Palaeozoic depositional basin in the Bonaparte Gulf area was disrupted by subsequent earth movements, and, at least near the southern margins, much of the original basin has been removed by erosion. In the Holocene (van Andel & Veevers, 1967) most of the preserved part of the basin was finally submerged, leaving only a small part on land. It is this small landward part of the original basin which was originally called the Bonaparte Gulf Basin, and this Bulletin deals with its southern part. The Ragged Range, Dillon Spring, and Mount Rob outliers have been isolated by erosion and faulting from the main part of the Basin to the north (see Fig. 67).

The Bonaparte Gulf Basin lies discordantly on the Precambrian Kimberley Block, and is bounded on the east by the Precambrian Halls Creek Mobile Zone (Traves, 1955, fig. 33*). The Kimberley Block is now being mapped by geologists of the Bureau and the Geological Survey of Western Australia, and discussion of the regional structural setting is deferred until this work has been completed.

Major Structural Subdivisions (Fig. 67)

The chief structural elements in the Bonaparte Gulf Basin are faults, probably normal faults, along which the main earth movements have occurred. The southern parts of the basin and the outliers are bounded by faults, and other parts of the basin, particularly the Pretlove Hills and the area to the north, are strike-

* Traves' Figure 33 must now be amended to show a broader expanse of 'Middle Palaeozoic' (Upper Devonian and Lower Carboniferous) sediments, bounded on the east by the Halls Creek Mobile Zone.

faulted. Folds are rare. A 22-mile-long inlier of Precambrian rocks in the Pincombe Range, the Pincombe Inlier, divides the Basin into two areas which Traves (1955, p. 9) called the Carlton Basin in the west and, following Matheson and Teichert (1948, p. 175), the Burt Range Basin in the east. The Burt Range Basin is co-extensive with the Burt Range Syncline, and the Carlton Basin consists of several structural units. The structural units described below are descriptive units related to present structure only, and are not to be confused with depositional provinces.

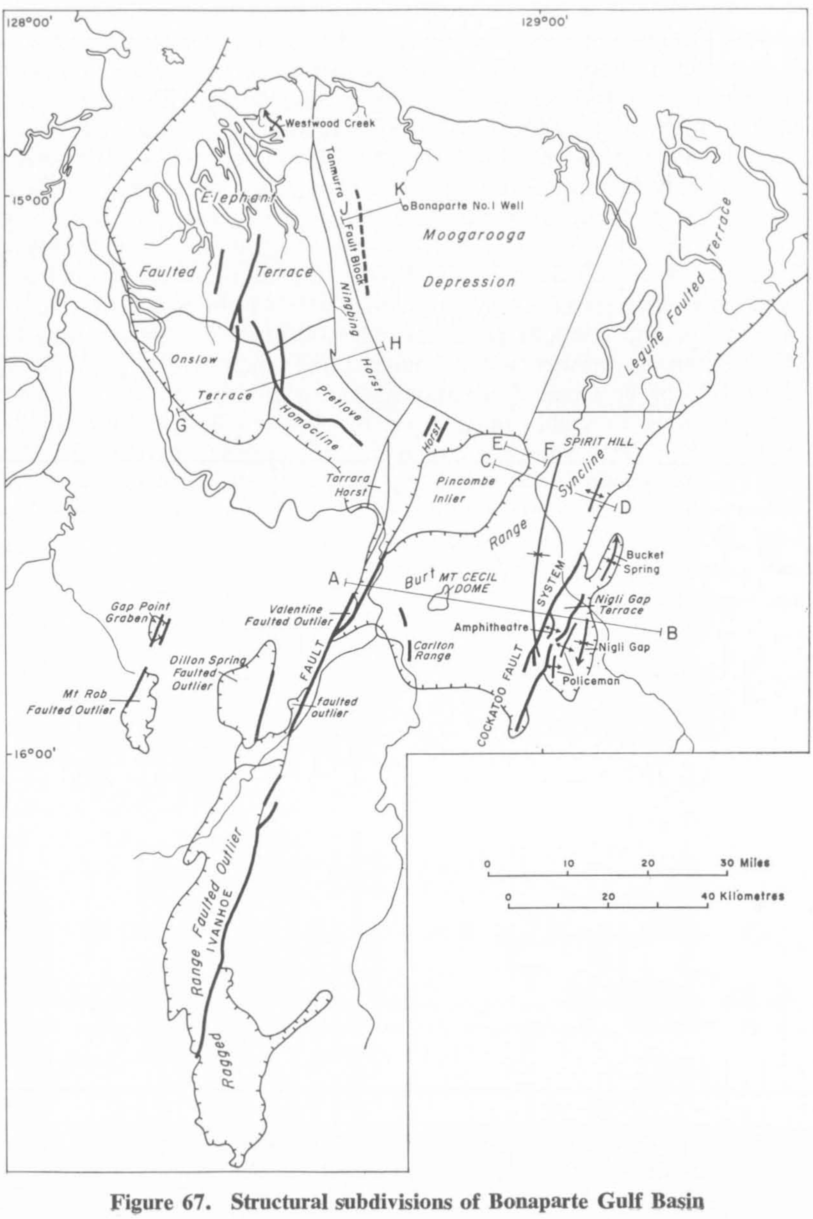


Figure 67. Structural subdivisions of Bonaparte Gulf Basin

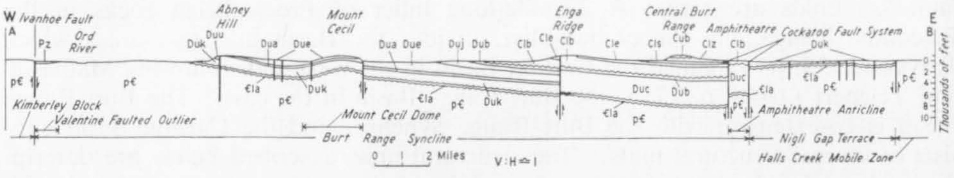


Figure 68. Section across Burt Range Syncline and Nigli Gap Terrace. (See Fig. 67 for location)

The *Burt Range Syncline* (Fig. 68) is a broad asymmetrical syncline with a northerly axis which almost coincides with the State border. The syncline extends northward from Cockatoo Spring to a line joining Sorby Hills and Alpha Hill; it is bounded on the east by the Cockatoo Fault System, on the southwest by the Ivanhoe Fault, and on the northwest by the Pincombe Inlier. The axis of the syncline is probably horizontal throughout except in the area south of the central Burt Range, where it pitches to the north at 10° to 20°. The Burt Range Syncline is distinguished from a homocline only by the reversal of dip, probably due to drag, along the eastern Cockatoo Fault System boundary. The easternmost part of the syncline is the *Amphitheatre Anticline,* which is bounded by faults of the Cockatoo System, and contains an estimated 6,000 feet of Upper Devonian and Lower Carboniferous sediments, the youngest of which is the Enga Sandstone, and a sliver of Border Creek Formation. The northern part of the syncline is poorly known owing to scanty outcrop on the western limb. According to our interpretation (Fig. 69), which is confirmed by seismic surveys (Bigg-Wither, 1963, pl. 22), the syncline is bounded on the east by the Cockatoo Fault System, and its eastern part is represented by the faulted Spirit Hill Anticline, which corresponds with the Amphitheatre Anticline to the south. Other minor sructures distinguished within the Burt Range Syncline are the Mount Cecil Dome and the Valentine Faulted Outlier.

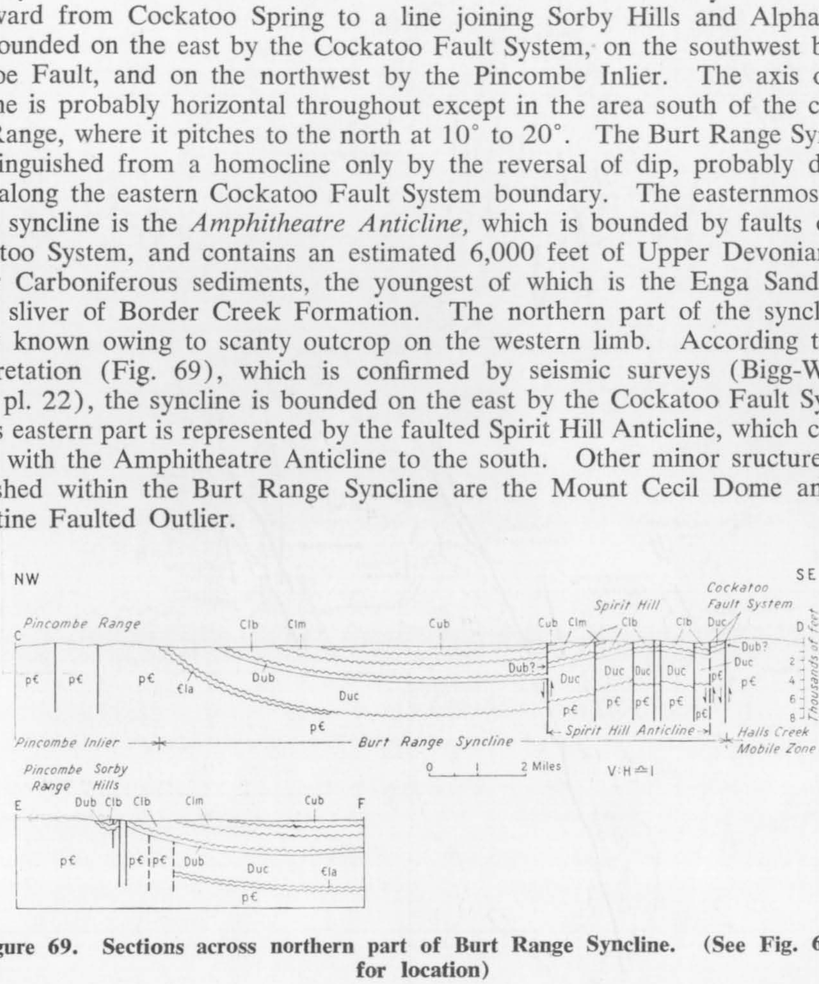


Figure 69. Sections across northern part of Burt Range Syncline. (See Fig. 67 for location)

The *Mount Cecil Dome* (see Fig. 11) is a dissected dome with a surface of silicified sandstone of the Cecil Member of the Cockatoo Formation, and a core of the Abney Member. The *Valentine Faulted Outlier,* named after the nearby Valentine Creek, contains fossiliferous Cambrian dolomite, and barren quartz sandstone, part of it identified as the Cockatoo Formation. The outlier is bounded on the west by the Ivanhoe Fault, and presumably rests on Precambrian rocks to the east. The *Spirit Hill Anticline* is a faulted anticline; it is described on page 96.

The *Carlton Range Fault* (Pl. 37, fig. 2; Matheson & Teichert, 1948, pp. 82-3, fig. 10) is a north-trending vertical fault along which the Kellys Knob Member is juxtaposed against Antrim Plateau Volcanics on the west.

The *Nigli Gap Terrace* is a sheet, 1,000 feet thick, of Cambrian Antrim Volcanics and Devonian Cockatoo Formation (Ragged Range and Kellys Knob Members) situated between the Burt Range Syncline on the west and the Halls Creek Mobile Zone on the east. Minor structures within the platform are the Nigli Gap Syncline, Bucket Spring Syncline, and Policeman Anticline.

The *Nigli Gap Syncline* is a south-pitching syncline south of Nigli Gap; it is faulted and bounded by faults. The *Policeman Anticline* to the south-southeast of Policeman Waterhole is also faulted and bounded by faults. The Ragged Range Member is probably exposed in the core in the south, and Kellys Knob Member elsewhere. Dips are very low. The *Bucket Spring Syncline* pitches to the north-northeast, and except for its southern part is known from photogeological interpretation only.

Our mapping shows that the *Ivanhoe Graben* of Matheson & Teichert (1948, p. 78, pl. 11) may be extended to the north-northeast from the Ord River to the track from Carlton to Point Spring; it is paralleled to the west by the *Tarrara Horst*. As shown in Figure 35, the southern part of the Ivanhoe Graben is bounded by concealed inferred faults each with a throw exceeding 3,000 feet. The trends of the faults are not known except that they lie within the northeast quadrant. To the north, the eastern edge of the graben is marked by the Pincombe Inlier, and the western edge by a fault 1 mile to the east of Tarrara Bar. The faulted Ningbing Limestone of the Jeremiah Hills and to the east is included in the Ivanhoe Graben because of its high stratigraphical position compared with the strata on either side, and because the main faults through it trend north-northeast. The outcropping Cambrian Clark Sandstone (Fig. 24) within the limestone is probably a horst.

The *Pretlove Homocline* includes the exposed Cambrian, Ordovician, and Devonian rocks of the Pretlove Hills and the exposed Devonian sediments of the Hargreaves Hills, all of which dip at 10° to 30° to the northeast. Figure 21 (from Kaulback & Veevers, 1968) is a cross-section through the Pretlove Hills, and part of Figure 70 shows a cross-section of the Hargreaves Hills. The homocline is strike-faulted; the Pretlove Hills consist of blocks, faulted down toward the southwest, and horsts; the Hargreaves Hills are a sequence of blocks uniformly faulted down towards the west-southwest, in the opposite direction to the dip.

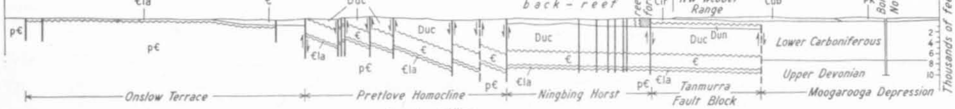


Figure 70. Section across western part of Bonaparte Gulf Basin. (See Fig. 67 for location)

The *Onslow Terrace* consists of exposed gently dipping Cambrian rocks, with a single graben of Cockatoo Formation (Kaulback & Veevers, 1968). The terrace is cut by a fault which trends northwards to Bald Hill. A southeast-trending branch of the fault marks the eastern edge of the Onslow Terrace; it continues southeastward to join the main fault in the Pretlove Hills.

The outcrop of the *Ningbing Horst* coincides with the Ningbing Range. The boundary faults are covered except at the southwest tip of the Ningbing Range, and are inferred from the stratigraphical relationships on the margins. The outcropping Ningbing Limestone is crossed by faults with small displacements, and is broadly folded into basins and domes (Fig. 31).

The *Elephant Faulted Terrace,* named after Elephant Hill, is poorly exposed. Faults are apparently the dominant structural element, and along faults in the Leichhardt Spring and Bald Hill areas the Cockatoo Formation is faulted against the Cambrian Skewthorpe Formation and Clark Sandstone. At Westwood Creek, a faulted anticline (Fig. 27) of the Cockatoo Formation pitches to the northwest. In the Shakespeare Hill area, faults cut the Cockatoo Formation into numerous blocks.

The *Tanmurra Fault Block* of the northwest Weaber Range is bounded by the fault along the eastern edge of the Ningbing Horst and by a subsurface fault revealed by seismic surveys (Petty Geophysical, 1964a).

The *Moogarooga Depression* is bounded on the west by this subsurface fault and on the southeast by the Legune Faulted Terrace. As shown by the Bonaparte No. 1 well, the thickness of Upper Devonian and Lower Carboniferous sediments in the depression is at least 10,000 feet.

The *Legune Faulted Terrace* is a northwesterly-sloping terrace crossed by north-trending faults. According to seismic surveys, it possibly contains 5,000 feet of Palaeozoic sediments near the coast.

The *Ragged Range Faulted Outlier* is crossed by the Ivanhoe Fault, which marks the eastern edge of the northern half of the outlier and the western edge of the southern half (Fig. 71, from Kaulback & Veevers, 1968).

The *Dillon Spring Faulted Outlier* is a well exposed half-basin of Cambrian volcanics and sediments and Cockatoo Formation bounded on the east by an unnamed fault. A similar smaller structure, 4 miles east of the Dillon Outlier, is truncated by the Ivanhoe Fault.

The *Mount Rob Faulted Outlier* of Cambrian volcanics and sediments and Cockatoo Formation(?) is bounded on the northwest by an unnamed fault. The *Gap Point Graben* is a graben of Cambrian and Upper Devonian(?) sediments bordered on the east by the scissor fault that truncates the Mount Rob Outlier.

Geophysics

A compilation of geophysical work conducted up to 1962 was made by Bigg-Wither (1963). The lack of sufficient contrast between the physical properties of the Precambrian and Palaeozoic rocks, and within the Palaeozoic rocks, reduced the value of reconnaissance geophysics, and much of the geophysical results in the southern Bonaparte Gulf Basin can be interpreted only by repeated reference to the geology. Further geophysical surveys have been carried out in the southern part of the basin since 1962, but, despite the use of new experimental methods,

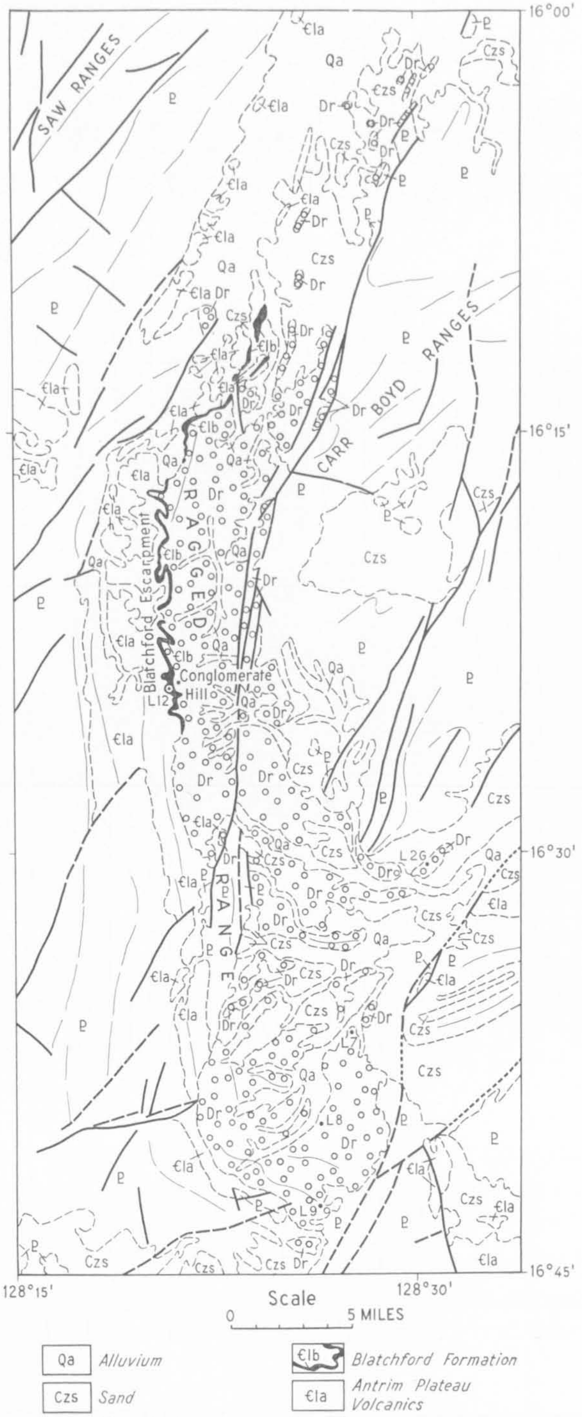


Figure 71. Geology of Ragged Range. (After Kaulback & Veevers, 1968)

TABLE 2 PHANEROZOIC STRUCTURAL HISTORY

Age	Legune Faulted Terrace	Moogarooga Depression	Tanmurra Fault Block	Ningbing Horst	Elephant Faulted Terrace	Onslow Terrace	Pretlove Homocline	Tarrara Horst	Ivanhoe Graben	Pincombe Inlier	Burt Range Syncline	Nigli Gap Terrace	Gap Pt Graben, Faulted Outliers of Mt Rob and Dillon Spring	Ragged Range Faulted Outlier
Quaternary	Uplift and erosion. Quaternary eustatic changes in sea level													
Miocene	SUBSIDENCE(?)													
Tertiary														
Cretaceous														
Jurassic														
Triassic														
Upper Permian		Faulting												
Lower Permian											Faulting			
Upper Carboniferous		Subsidence									Sub-sidence			
Namurian		Uplift and erosion												
Visean late							Sub-sidence (?)				Uplift and erosion			
Visean mid		Subsidence	Subsidence				Subsidence				Subsidence with intermit-tent faulting and uplift			
Visean early				Uplift and erosion			Uplift and erosion							
Tournaisian late	Sub-sidence						Tilting, faulting, uplift, and erosion			Subsidence				
Tournaisian mid		Subsidence, non-deposition or erosion	Subsidence								Uplift and erosion			
Tournaisian early							Subsidence							
Famennian		Subsidence			Subsidence(?)				Sub-sidence	Land	Subsidence			
Frasnian	Faulting and Sub-sidence	Sub-sidence	Subsidence							Uplift and erosion	Faulting and subsidence			
Middle Devonian to Middle Ordovician		UPLIFT AND EROSION												
Lower Ordovician, Upper Cambrian, Middle Cambrian			Subsidence(?)		SUBSIDENCE			Subsidence(?)					Sub-sidence at Gap Pt; Sub-sidence	Sub-sidence (?)
Lower Cambrian late		Erosion												Sub-sidence
Lower Cambrian early	Uplift and erosion; Extrusion of basalt and deposition of associated sediments													

the results generally remain poor. One notable result is the mapping of a subsurface fault in the area west of Bonaparte Nos 1 and 2 by the Petty Geophysical Engineering Company (1964a). Other surveys since 1962 (all of them subsidized by the Commonwealth Government) are Petty (1964b, 1965a,b) and United Geophysical Corporation (1964). By contrast, the seismic surveys of the offshore Bonaparte Gulf Basin (Vale & Jones, 1967) have been satisfactory.

Sequence of Structural Events (Table 2)

Epi-early Lower Cambrian: Epeirogenic uplift and warping.

Late Lower Cambrian: Subsidence in Ragged Range, deposition of Blatchford Formation.

Early Middle Cambrian: Subsidence continuing to end of Lower Ordovician in outliers and western part of basin. Intermittent faulting during deposition.

Middle Ordovician to Middle Devonian: Uplift at an undetermined time within this interval, and subsequent erosion.

Frasnian: Subsidence of basin along marginal faults, and intermittent faulting during deposition.

Famennian: Continued subsidence with less intense or little faulting.

Early Tournaisian: Tilting, faulting, and rapid uplift and erosion of Pretlove Homocline. Epeirogenic uplift and erosion in Burt Range Syncline.

Mid-Tournaisian: Subsidence of Burt Range Syncline, Legune Terrace, Tanmurra Fault Block, and Ningbing Horst and, slightly later, subsidence of the edge of the Pretlove Homocline.

Late Tournaisian: Uplift of Ningbing Horst and Pretlove Homocline and subsequent erosion; intermittent uplift of Burt Range Syncline causing erosion or non-deposition. Subsidence in Moogarooga Depression and continued subsidence of Legune Terrace and Burt Range Syncline.

Mid-Visean: Subsidence of Ningbing Horst, Tanmurra Fault Block, edge of Pretlove Homocline, and continued subsidence of Moogarooga Depression, probably continuing to late Visean.

Namurian: Uplift and erosion.

Rest of Upper Carboniferous to Lower Permian: Subsidence.

Upper Permian: Faulting.

Miocene: Possibly subsidence.

Post-Miocene: Uplift and erosion.

The chief events are:

(a) The late Lower or early Middle Cambrian subsidence that preceded Cambrian marine deposition;

(b) Middle Ordovician to Middle Devonian uplift and erosion;

(c) Early Frasnian differential movements initiating Upper Devonian to Lower Carboniferous marine deposition;

(d) Early to middle Tournaisian faulting, uplift, and erosion, most intense in the southwestern part of the basin;

(e) Namurian uplift and erosion;

(f) Later Upper Carboniferous to Lower Permian subsidence initiating deposition of Upper Carboniferous/Lower Triassic sequence;
(g) Upper Permian faulting.

The age of the final episode of faulting is not precisely known; it probably immediately antedates the Upper Permian unconformity in the Port Keats area.

Some of the events probably correspond in time to more widespread earth movements, and even (c) for example probably coincides with the epi-Middle Devonian Tabberabberan Orogeny of eastern Australia. However, Table 2 shows that most of the events are restricted to a few areas within the Bonaparte Gulf Basin itself and, at least during the Upper Devonian and Lower Carboniferous, span an almost continuous range of time, so that, with the exception of the initial early Upper Devonian event, none of the events can be singled out as a major widespread earth movement.

GEOLOGICAL HISTORY

The following description of the geological history is a preliminary account only, and some of the interpretations given will probably be revised in the light of laboratory work now in progress.

A reconstruction of the solid geology of the area immediately before the deposition of the Cockatoo Formation is shown in Figure 72a. The pre-Cockatoo Formation surface consisted of Precambrian rocks in the east and southeast, and passed through Lower Cambrian volcanics and sediments to Upper Cambrian and Lower Ordovician sediments in the northwest. Except in a few places, the Cambrian and Ordovician sediments were subhorizontal. Because the thickness of the Cambrian and Ordovician sedimentary sequence exceeds 4,000 feet, structure dominated over morphology in determining this distribution. Whether the regional structure was a homocline with a low westerly dip, or a fault structure, or a combination of both, is not known.

A marine invasion accompanied the earth movements which affected the area in the early Upper Devonian (Fig. 72b). In the platform conglomeratic province, conglomerate and red sandstone were deposited at the foot of high ground along the eastern margin of the basin, and at the foot of the southern flank of the Pincombe Inlier. The conglomerate passed into white sandstone in the platform carbonate province, which in turn possibly passed laterally into dark siltstone and shale in the basinal province. A low shoreline in the northwest (platform carbonate province) is postulated to account for the deposits of thick sandstone (Kellys Knob Sandstone Member) in this part of the basin. The land to the west shed sand and probably also mud, but no gravel. The exact position of the shoreline is unknown, but the estimated position is as shown in Figure 72b. The southern continuation of the shoreline is also unknown. The basal sandstone of the Cockatoo Formation in the Gap Point and Dillon Spring Outliers is close enough to the eastern margin of the basin to have come originally from this side, and the shoreline may have lain a considerable distance to the west.

Islands were dotted along the northeastern coastline. The Pincombe Inlier was a small island with a high south coast (as shown in Fig 72b) or with south-flowing drainage. Conglomerate was deposited along the southern shore, and quartz sandstone to the north and northeast.

The postulated deposition of dark shale and siltstone in the basinal province anticipated Famennian and Lower Carboniferous depositional patterns.

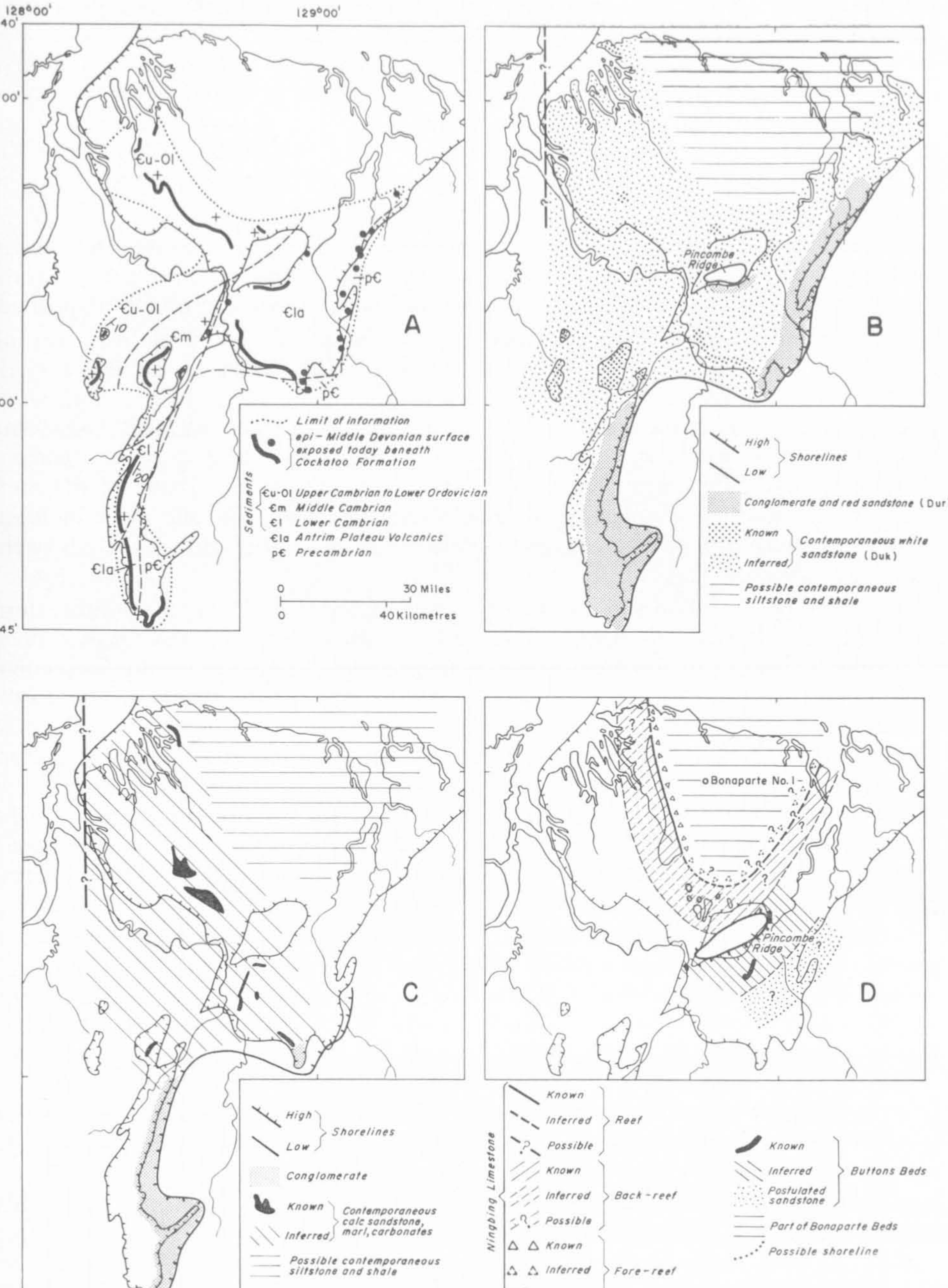


Figure 72. Reconstructions of the Devonian of the Bonaparte Gulf Basin. (a) Epi-Middle Devonian palaeogeology; (b) Basal Frasnian; (c) Middle Frasnian; (d) Famennian

A waning supply of coarse sand later in the Frasnian (Fig. 72c) was accompanied by the spread of calcareous deposits over the platform area previously covered by sand, so that coarse terrigenous detritus was deposited along the eastern shore only. The postulated western shore intermittently yielded sand, and in a period of abated sand deposition reefs were deposited at least in the Westwood Creek area. The reworked Ordovician conodonts in the Westwood Member (and in the Ningbing Limestone) indicate the presence of Ordovician sediments in the source area. We postulate continued deposition of shale and siltstone in the basinal province.

Following this phase of deposition, the surrounding land was uplifted and a thick layer of sand (Cecil Sandstone Member) was deposited over the platform except in the basinal province, where shale and siltstone were probably deposited.

A second phase of carbonate deposition took place on the platform during the Famennian (Fig. 72d), probably due in part to the reduced supply of terrigenous detritus. Sediments were deposited in four belts: dark siltstone and shale (Bonaparte Beds) in the basinal province; a carbonate reef complex (Ningbing Limestone) in the platform carbonate province and possibly also on the eastern side; sandy and silty limestone (Buttons Beds) on the landward side of the reef; and a postulated belt of quartz sandstone along the shore. In one place at least, the northeastern tip of the emergent Pincombe Inlier, the Buttons Beds were deposited along the shore.

During the late Famennian to early Tournaisian (Fig. 73a), the southeastern platform was uplifted (probably along faults) and eroded, and the sea withdrew to a shoreline north of the emergent Pincombe Inlier. This uplift and subsequent migration of the shoreline apparently did not affect the growth of reef on the northwestern platform. The step fault shown in the reconstructed latest Famennian to earliest Tournaisian surface (Fig. 73a) is postulated because the Burt Range Formation paraconformably overlies the early Famennian(toII-toIII) Buttons Beds to the west of the fault line, and the Frasnian(toI) Cockatoo Formation to the east and northeast of the line; the Buttons Beds are unknown east and northeast of the fault, where the Burt Range Formation probably overlies eroded Frasnian(toI) Cockatoo Formation.

In the early Tournaisian (Fig. 73b), the sea returned to the southeastern platform, covering the eroded Buttons Beds and Cockatoo Formation and at least lapping the Pincombe Inlier. Marine sandstone, deposited close to the shore, passed seawards into calcareous sandstone which in turn passed into calcarenite (all Burt Range Formation), and finally into shale (Bonaparte Beds) in the basinal province. The sandstone in the Sorby Hills, at the tip of the Pincombe Range, is an exception; the sand could have been derived from the Pincombe Inlier, or it could have come from the east near Spirit Hill. At this time at Spirit Hill there were at least two periods of erosion followed by the deposition of quartz sandstone containing pebbles and boulders. The early Tournaisian shore intermittently crossed the Spirit Hill area, but for the sake of simplicity it is not shown in Figure 73b. The only deposit of this age known on the northwestern platform is reef limestone from a single locality near Ningbing. The reef probably extended northwards along the trend of the Famennian reefs, and was flanked by back-reef and fore-reef limestone, with back-reef presumably passing into calcareous sandstone and sandstone towards the shore, and fore-reef limestone into dark shale and siltstone towards the basinal province.

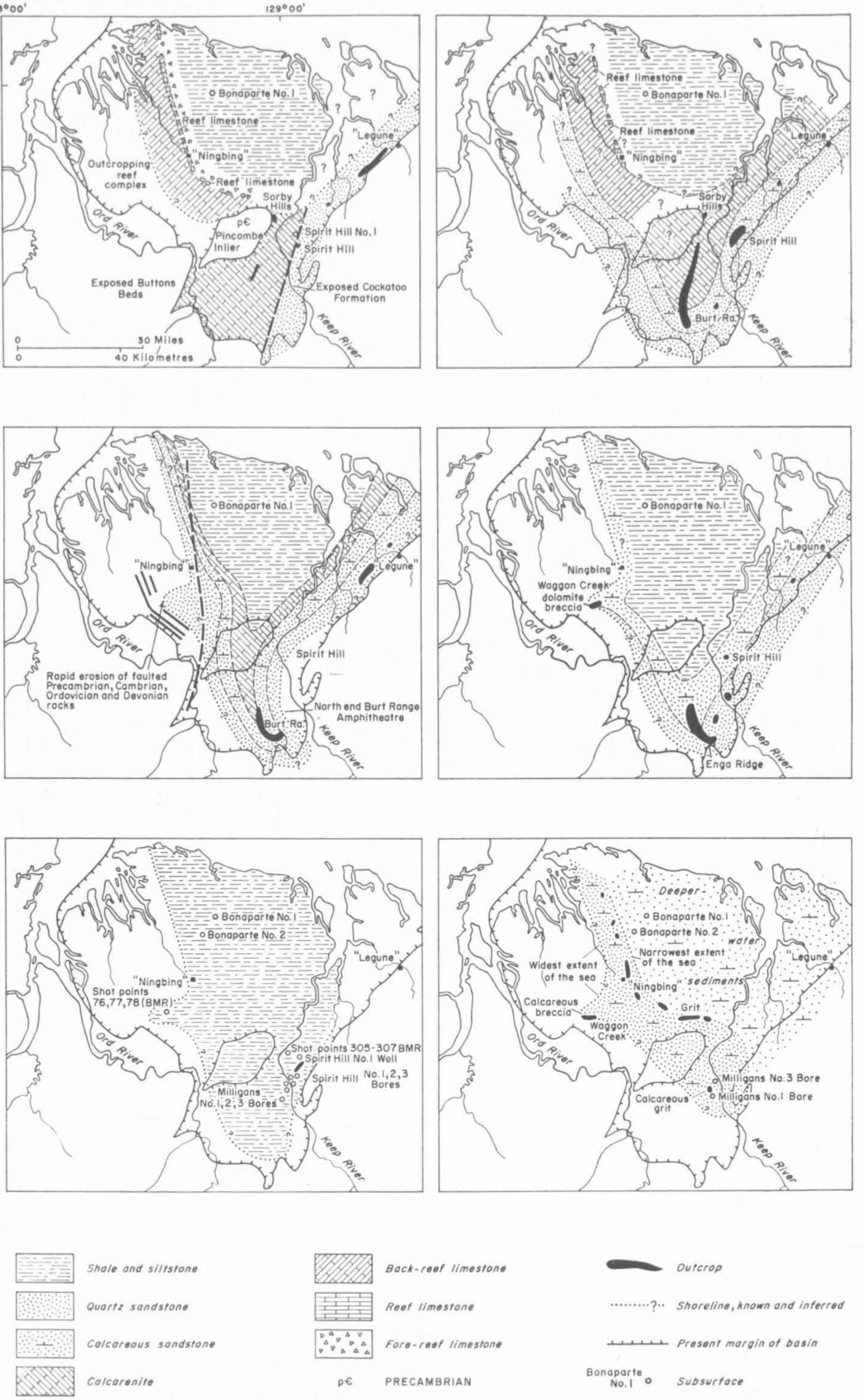


Figure 73. Reconstruction of the Lower Carboniferous of the Bonaparte Gulf Basin. (a) latest Famennian to earliest Tournaisian: (b) early Tournaisian (CuI to lowermost CuII$_\alpha$); (c) middle Tournaisian (CuII$_\alpha$); upper Burt Range Formation time; (d) middle Tournaisian (CuII$_\alpha$); basal Enga Sandstone time; (e) early Visean (CuII$_\delta$); (f) late Visean (CuIIIβ-$_\delta$).

In the middle Tournaisian (CuII$_\alpha$ or upper Burt Range Formation time) (Fig. 73c) the northwestern platform was profoundly faulted, tilted, and uplifted. Rapid erosion of the Precambrian, Cambrian, Ordovician, and Devonian rocks (mainly sandstone, with some dolomite and basic volcanics) supplied vast quantities of detritus which, we postulate, was deposited at the mouth of the ancient Waggon Creek valley, south of Ningbing. The valley may have been a gap in the reefs as early as the Famennian or may have been formed by the erosion in the middle Tournaisian. A barrier formed by the reef complex to the north probably funnelled detritus through the Waggon Creek valley to the shore (Veevers & Roberts, 1966). The areas of calcareous sand and calcarenite shown along the northwestern platform (Fig. 73c) are conjectural.

In the Burt Range area on the southeastern platform, deposition continued without interruption, but movements on faults or upwarping to the east and northeast caused uplift and erosion, particularly at Spirit Hill and at the northern end of the Burt Range Amphitheatre. The shore was thus west of these localities (Fig. 73c), but the position of the shoreline on the southwestern margin of the basin is conjectural.

Slightly later in the middle Tournaisian (basal Enga Sandstone time) (Fig. 73d), the area between the Burt Range Amphitheatre and Spirit Hill and probably the whole eastern margin of the basin sank beneath the sea, and the belts of sediment—sand, calcarenite and sandy limestone, and shale—shifted short distances towards the east and south. The sand became coarser towards the shore and at one locality on the Keep River contains quartzite boulders. The middle Tournaisian carbonate sequence is thinner than the earlier Tournaisian carbonate sequence, as reflected by the narrower band of sandy limestone and calcarenite.

At Waggon Creek, the sea lapped on to the cliffs of dolomite and sandstone (Cockatoo Formation) and deposited a dolomite breccia (unnamed). This marks a definite point on the western shore, which we postulate extended northwards along the eastern margin of the Famennian and Lower Tournaisian reef complex. We have no knowledge of the sediments deposited along this shore.

Alternating deposition of sand and calcarenite (Enga Sandstone, Septimus Limestone, and Zimmermann Sandstone) continued on the southeastern platform until the late Tournaisian or early Visean. Deposition of the different rock types was probably determined by the supply of terrigenous sediment.

Early in the Visean (Fig. 73e), parts of the southeastern platform, and particularly the area around Spirit Hill, emerged and were stripped of the Zimmermann Sandstone and Septimus Limestone, and most of the Enga Sandstone. The sea returned shortly afterwards (CuII$_\delta$), and also re-entered the Waggon Creek valley, depositing dark shale and siltstone. The clay minerals in the Milligans Beds in the Spirit Hill No. 1 well suggest that the shale was deposited close to the margin of the basin (Dr F. C. Loughnan, pers. comm.). This is supported by the occurrence of conglomerates in the Milligans Beds in the same well, and hence we have termed the shale a nearshore shale (Fig. 73e). Loughnan has not examined shale from Waggon Creek valley, but it too occupies a nearshore position. The dark shale in Bonaparte No. 1 has a slightly different clay content, and according to Dr Loughnan was deposited away from the influence of land; it is termed an offshore shale (Fig. 73e). According to Duchemin & Creevey (1966) the Visean shale in the Kulshill No. 1 well is essentially the same as the shale in Bonaparte No. 1.

Figure 38 shows that we interpret the nearshore and offshore shales as belonging to a single shale body, and the nearshore shales as tongues projecting from the central mass. Because the nearshore shales are close to the coastline it seems likely that the widespread distribution of shale resulted from the absence of coarse detritus from the deeply eroded source area, rather than from a widespread marine transgression.

A marked thickening of shale in the basinal province indicates accelerated subsidence later in the Visean (Fig. 38). On the northwestern platform a Visean (CuII$_{\delta}$-CuIII$_{\alpha}$) calcarenite (Utting Calcarenite), equivalent to part of the thick shale sequence, was deposited close to the shore (not shown in Fig. 73e, which shows the immediately preceding time). Some beds in the calcarenite contain coarse sand and conglomerate pebbles which must have been washed in from the land area to the west.

In the late Visean (Fig. 73f) the sea regressed, and coarse alluvial sand was deposited in a wide belt parallel with the western and southwestern shores. With the return of the sea a short time afterwards these coarse sands were reworked and incorporated in beach deposits (Burvill Beds). Sea level probably fluctuated during this time; Figure 73f gives an indication of the narrowest and widest extent of the sea. As the sea moved into the Waggon Creek valley it incorporated the alluvial sediments into a basal pebbly sandstone, which was consolidated as beach rock, and then undercut the nearby cliffs of dolomite and sandstone (Cockatoo Formation). The sandstone was friable and easily eroded, leaving exposed cliffs and stacks of dolomite. These were undermined, collapsed into a jumbled mass of blocks, and were mixed with boulders of quartzite and coarse sand brought down and dumped as piedmont deposits in valleys. These deposits (Waggon Creek Breccia) are described in more detail by Veevers & Roberts (1966).

The movement of the sea into the Waggon Creek valley was probably caused by local subsidence rather than by a widespread marine transgression. Sea level does not seem to have risen throughout the basin, and from the nature of the sediments in Bonaparte Nos 1 and 2 wells (limestone and calcareous sandstone) it seems likely that there was actually a regression, so that, for the first time in the Devonian and Carboniferous, the dark shale in the basinal province was covered by rocks characteristic of the platform. We assume that the basinal province moved farther out to sea.

In the latest Visean or earliest Namurian the source area provided a supply of quartz sand (Point Spring Sandstone), which was deposited in approximately the same areas as the late Visean beach deposits. The sandstone appears to be a regressive deposit and contains marine beds as well as coarse cross-bedded unfossiliferous beds which could be non-marine.

Between the early Namurian and late Upper Carboniferous the basin was uplifted and eroded. The deepest erosion was in the south, particularly in the Burt Range, which suggests that the uplift was effected by upwarping or upfaulting in the south. These or later movements also rejuvenated the source area, and coarse terrigenous sediments, beginning a depositional episode extending from the late Carboniferous to early Triassic, accumulated in continental deposits (Border Creek Formation) across a large part of the basin. These rocks were overlain by Lower Permian glacial deposits, and still later by Permian and Lower Triassic paralic sediments. Large normal faults, the chief structural elements in the eastern part of the basin, were formed during the Permian.

GEOMORPHOLOGY

by J. Hays

In a study of mature erosion surfaces in the northern part of the Northern Territory, Hays (1967) has identified the Ashburton, Tennant Creek, Wave Hill, and Koolpinyah Surfaces, each associated with major or minor periods of lateritization. The pre-Cretaceous Ashburton surface is absent from the Bonaparte Gulf Basin and there are only a few doubtful examples of the late Cretaceous to mid-Tertiary Tennant Creek Surface. The mid(?)-Tertiary to Recent Wave Hill Surface and the late(?) Tertiary to Recent Koolpinyah Surface are both well developed in the Bonaparte Gulf Basin.

Koolpinyah Surface

The Bonaparte Gulf Basin may be divided into two similar geomorphological provinces separated by the joint estuary of the Victoria and Fitzmaurice Rivers.

The northern province consists of most of the Western Plains of the Katherine-Darwin area (Noakes, 1949) and is part of the type area of the Koolpinyah Surface. From Point Blaze south to the Port Keats area the surface has extremely low relief, broken by a few residuals of older surfaces. It is a complex multicyclic surface, consisting of remnants of the Wave Hill Surface, surfaces of sedimentation, and young erosional surfaces which show local geological control. Extensive alluviation above present base level in drowned valleys points to a former rise in sea level, perhaps as a result of Pleistocene eustatism (Christian & Stewart, 1953). This was followed by a recent fall of about 20 feet as indicated by the depth of incision of some of the streams on the plains, stranded beach ridges (originally permanent berms), and emerged beaches and strandlines. However, the full history of the plains is not known, and as a few of the smaller streams are lost in swamps before reaching the sea, it is probable that several changes of sea level, perhaps produced by local warping, are involved.

Deposits of detrital laterite are abundant at several levels in the area. Some of the deposits rest upon the pallid zone of a truncated lateritic profile to simulate a complete standard lateritic profile of ferruginous laterite, mottled zone, and pallid zone.

Over most of the area the Koolpinyah Surface extends inland from the coast for about 40 miles, at heights ranging from sea level to about 100 feet above sea level, with gradients from nil to 2 or 3 feet per mile. It terminates against a scarp, 200 to 500 feet high; the scarp, in places, is so regular that it may be mistaken for a fault scarp, but in other places it is discontinuous and irregular because of the extension of the surface up major valleys.

In a few coastal areas, cliffs have been formed on residuals of a shallowly dissected Wave Hill Surface. They appear to be remnants of broad gently undulating irregular divides between the Finniss, Daly, Moyle, and Fitzmaurice Rivers. Most of the residuals are so low that they may be regarded as part of the Koolpinyah Surface, but higher residuals occur in the north and south. The northern part of the Bonaparte Gulf Basin is almost completely separated from the Victoria-Fitzmaurice estuary by a large residual in the Port Keats/Pearce Point area. Coalescing panplains along tributaries of the Moyle and Fitzmaurice Rivers, east of the residual, form the main link between the northern and southern parts of the basin.

The southern part extends from the Victoria River to Cambridge Gulf and consists largely of alluvial plains and swamps, with subordinate young erosional surfaces, from which rise residuals of older surfaces. The residuals generally have a relief of 500 to 1,000 feet. The plains and swamps range in height from sea level to about 120 feet, 60 miles from the coast, and the mean gradient is less than 2 feet per mile.

The southern part differs from the northern in several respects, although the general history appears to have been the same. The recent alluviation was much more extensive in the south, so that the surface appears to be much less complex. Nevertheless, large irregular 'islands' of detrital laterite stand 2 or 3 feet above the level of the alluvium, and attest to the former existence of detrital laterite plains. Detrital laterite occurs beneath the alluvium in several areas.

Young erosional surfaces are represented by rock pavements at alluvium level and by benches formed by local geological control on the sides of hills. A few flat-topped hills in accordance with the benches on adjacent hills are also attributed to local structural control and have no regional significance.

Wave Hill Surface

The Wave Hill Surface has been traced continuously from its type area on Wave Hill station north to Legune station and along the edge of the northern province of the Bonaparte Gulf Basin. It extends into the basin as scattered residuals with accordant summits, and dips generally to the east. Local variations have been produced by gentle northwest warping so that the Wave Hill Surface merges into the Koolpinyah Surface between the Daly River and Port Keats area and stands at least 100 feet above it farther north and south. Near Port Keats, the Wave Hill Surface is represented by a large partly dissected residual rising from about 200 feet above sea level near Port Keats to about 300 feet near the Fitzmaurice River; it has an area of about 300 square miles. The projection of this residual to the south across the Fitzmaurice and Victoria Rivers is in accordance with residuals of the Wave Hill Surface near Legune station, which range from 500 to 600 feet above sea level. Deposits of detrital laterite are abundant on the surface in the northern province, and in many places they rest upon truncated lateritic profiles and simulate complete profiles.

In the southern part of the Bonaparte Gulf Basin, all the highest hills observed, with the exception of House Roof Hill, appear to be in accordance and to indicate the presence of an old mature land surface 1,000 feet above sea level in the south, tilted north or northeastwards and so completely dissected that only scattered residuals, such as the Burt and Pincombe Ranges and Mount Septimus, remain. Aerial observation indicated that this must be either the Wave Hill or Tennant Creek Surface. All the accordant summits except Mount Septimus are capped by ferruginous sandstone on which a standard lateritic profile would not necessarily be formed. Consequently, the surface represented could not be identified, although it appears to be in accordance with the Wave Hill Surface identified on Legune station.

Confirmation of this was obtained at Mount Septimus, which, unlike the other hills examined, was capped by lateritized sediments and superficial deposits. A capping of a few feet of white to buff porcellanite(?), ironstained in parts, is overlain by detrital laterite which consists of fragments of ferruginous laterite and sparse sandstone pebbles cemented by iron oxides. The porcellanite is similar to that formed from Cretaceous shale in the pallid zone of lateritization in the Darwin area and represents a truncated standard lateritic profile. The cover of detrital laterite, which is leached in places near its base, combines with the truncated profile to simulate a complete standard lateritic profile. As the flat top of Mount Septimus is in accordance with the summits of the surrounding hills, these must represent a surface younger than the Tennant Creek Surface, i.e. the Wave Hill Surface.

Tennant Creek Surface

The Bonaparte Gulf Basin appears to have been formed in an area from which most of the Tennant Creek Surface has been removed by the encroaching Wave Hill Surface, and very few traces of it have been found. A few residuals stand about 300 feet or less above the Wave Hill Surface in the northern province, particularly in the area southeast of Port Keats. Some of these are in accordance with remnants of the Tennant Creek Surface to the east of the Bonaparte Gulf Basin; the rest have been eroded below this level.

House Roof Hill, 1,265 feet above sea level, between Kununurra and Wyndham, is the only Tennant Creek Surface residual identified in the southern province. Other residuals may be present, but they cannot be identified because of the lack of adequate topographic data and the absence of a standard lateritic profile.

ECONOMIC GEOLOGY

Petroleum Prospects

The only known occurrence of petroleum in the basin was found in AOD Bonaparte No. 2 (Le Blanc, 1965, unpubl.). A drill-stem test of a sandstone bed in the Bonaparte Beds at 4,716 to 4,726 feet produced a flow of gas at a maximum rate of 1,540,000 cubic feet per day. The gas consisted mainly of methane, with 8 to 14 percent of higher hydrocarbons. Drill-stem tests of other parts of the well failed to yield hydrocarbons. The only indications of hydrocarbons in AOD Bonaparte No. 1 were 'moderate "kicks" of gas with a high methane content which were recorded on the gas detector following each trip within the interval 5,000 feet to 10,283 feet' (Le Blanc, 1964, unpubl.). The gas occurrences indicate the low porosity and permeability. The dominant shale is considered an excellent source rock and seal for the interbedded sandstones, which provide potential reservoirs. The juxtaposition of the shale and porous sandstone or limestone by facies changes or by faulting at the edge of the Moogarooga Depression makes this a favourable zone for the accumulation of petroleum. If a favourable structure could be found in the Tanmurra Fault Block (Fig. 70), this would be an attractive place to drill. The area around Point Spring may also be prospective because of the possibility of sealed porous pinchouts against the Pincombe Inlier and reefs. Increased permeability would be expected in the area 5 miles southeast of Ningbing homestead, where we believe the main drainage in Tournaisian times flowed into the area and dropped large volumes of porous sand. Finally, if the reefs of the Ningbing Limestone continue northward along the strike under a suitable cap, or dip into the edge of the Moogarooga Depression, they would be potential reservoirs.

Lateral facies changes and fault structures are probably the chief means whereby petroleum has accumulated in the outcrop area; its preservation there probably depends on the presence of an effective seal, such as is provided by the Milligans Beds and perhaps also by parts of the carbonate units.

Limestone

Some of the beds in the Ningbing Limestone consist of high-grade limestone; large reserves are available.

Metals

Pyrite is a common constituent of much of the shale in the Bonaparte Nos 1 and 2 and Spirit Hill No. 1 wells; in the percussion holes near Milligans Lagoon, grains of framboidal pyrite or pyritomorphs have been found by P. J. Jones (BMR, pers. comm.). In the Burt Range Syncline, and in particular at Spirit Hill, the carbonates along many faults are mineralized: Allen (1956, unpubl.) has recorded cerussite, psilomelane, and rhodochrosite in a sample of limestone from Spirit Hill.

Groundwater

Probably because surface water is abundant in many parts of the area, few bores have been drilled for water, and the only information is from seismic shot-holes and oil exploration wells. Spirit Hill No. 1 was completed as an artesian well, with a flow of 100 gallons per hour of water with 332 parts per million of soluble salts from a depth of 850 feet (Hare et al., 1961, unpubl.) at the unconformity between the Burt Range Formation and the overlying Milligans Beds. This is the only known record of pressure water in the basin.

Shallow groundwater of unknown quality was found in some seismic shotholes in the Moogarooga Depression, but most of them were dry. The only area that consistently yielded water in shallow shotholes (100 ft or less) was situated 4 miles northeast of Ningbing homestead. No flows of water were recorded in Bonaparte Nos 1 and 2. The water supply for Bonaparte No. 2 was obtained from a bore 2½ miles southwest of the well; the aquifer was at 80 feet, and water was pumped at a rate of 450 gallons per hour.

Kemezys (1966) has described a hydrological survey of the saline coastal alluvium of Legune station. This alluvium underlies well grassed treeless plains which are only a few feet above the tidal mud flats (Pl. 38, fig. 2). Bores down to 1,000 feet yielded good flows of water, but it was too saline (10,000-60,000 ppm) for pastoral purposes. A few bores sited in the timbered, hilly, and sandy terrain which marks the landward margin of the plains yielded flows of suitable water.

Springs

Most of the numerous springs in the area issue along faults. An exception is the northern part of the area, between Westwood and Yow Creeks (Map 1), where springs issue at the boundary between sandy eluvium and the grassed plains behind the tidal mud flats (Pl. 38, fig. 1).

Ochre

Traves (1955, pp. 105-6) has described the ochre mine 8 miles west of Alligator Spring. No further information is available, except that we identify the host rock as the Ragged Range Member of the Cockatoo Formation.

ACKNOWLEDGMENTS

We express our gratitude to M. J. Dando, W. Dunn, G. C. McGregor, and R. H. Otway, for their whole-hearted assistance in the field; to Bureau field parties working in adjoining areas, for co-operation; to our visitors, R. L. Folk, P. E. Playford, P. E. Cloud Jr, and G. A. Thomas, for valuable criticism; to geologists of Australian Aquitaine Petroleum, in particular M. Zimmermann, A. Duchemin, P. Michoud, M. Eyssautier, S. Rueff, and P. Haskins, for fruitful collaboration in the field and stimulating discussion in the office; to Anacapa Oil Corporation, in particular W. Jauncey, who made it possible to visit Rocky and Pelican Islets; to E. Rod, for helpful discussion; and finally to the Public Works Department, Kununurra, in particular A. Siggins, for information and hospitality. We thank K. S. W. Campbell, A. Duchemin, and J. M. Dickins for criticizing the final manuscript.

REFERENCES

PUBLISHED

BRADY, T. J., JAUNCEY, W., and STEIN, C., 1966—The geology of the Bonaparte Gulf Basin. *J. Aust. Petrol. Expl. Ass.*, 1966, 7-11.

BRANSON, E. B., 1944—The geology of Missouri. *Univ. Mo. Stud.*, 3, 1-535.

CHRISTIAN, C. S., and STEWART, G. A., 1953—General report on survey of Katherine-Darwin region, 1946. *Sci. ind. Res. Org., Canberra, Land Res. Ser.* 1.

COLLINSON, C., SCOTT, A. J., and REXROAD, C. G., 1962—Six charts showing biostratigraphic zones and correlations based on conodonts from the Devonian and Mississippian rocks of the Upper Mississippi Valley. *Ill. geol. Surv. Circ.* 328, 1-32.

DICKINS, J. M., ROBERTS, J., and VEEVERS, J. J., 1968—Permian and Mesozoic geology of the northeastern part of the Bonaparte Gulf Basin. *Bur. Miner. Resour. Aust. Rep.* (in prep.).

DRUCE, E. C., 1968—Devonian and Carboniferous conodonts from the Bonaparte Gulf Basin, northwestern Australia, and their use in international correlation. *Bur. Miner. Resour. Aust. Bull.* 98.

DUNBAR, C. O., and RODGERS, J., 1957—PRINCIPLES OF STRATIGRAPHY. *N.Y., Wiley.*

GUILLAUME, R. E. F., 1966—Petroleum geology in the Bonaparte Gulf Basin, N.T. *8th Comm. Min. metall. Cong.*, 1965, 5, 183-96.

HAYS, J., 1967—Land surfaces and laterites in the north of the Northern Territory. *In* JENNINGS, J. N., and MABBUTT, J. A., LANDFORM STUDIES FROM AUSTRALIA AND NEW GUINEA. *Canberra, Aust. Nat. Univ. Press,* 182-210.

HILL, DOROTHY, 1954—Coral faunas from the Silurian of New South Wales and the Devonian of Western Australia. *Bur. Miner. Resour. Aust. Bull.* 23.

JONES, P. J., 1968—Upper Devonian Ostracoda and Eridostraca from the Bonaparte Gulf Basin, northwestern Australia. *Bur. Miner. Resour. Aust. Bull.* 99.

JONES, P. J., and DRUCE, E. C., 1966—Intercontinental conodont correlation of the Palaeozoic sediments of the Bonaparte Gulf Basin, northwestern Australia. *Nature,* 211 (5047), 357-9.

KAULBACK, J. A., and VEEVERS, J. J., 1968—Cambrian and Ordovician geology of the southern part of the Bonaparte Gulf Basin. *Bur. Miner. Resour. Aust. Rep.* 109 (in press).

KEMEZYS, K. J., 1966—Saline coastal alluvium. *Water Resources Newsletter,* 6, 30-1.

LLOYD, A. R., 1967—A possible Miocene marine transgression in northern Australia. *Bur. Miner. Resour. Aust. Bull.* 80.

MATHESON, R. S., and TEICHERT, C., 1948—Geological reconnaissance in the eastern portion of the Kimberley Division, Western Australia. *Dep. Min. W. Aust. Ann. Rep.* 1945, 73-87.

MCWHAE, J. R. H., PLAYFORD, P. E., LINDNER, A. W., GLENISTER, B. F., and BALME, B. E., 1958—The stratigraphy of Western Australia. *J. geol. Soc. Aust.*, 4(2).

NOAKES, L. C., 1948—A geological reconnaissance of the Katherine-Darwin Region, Northern Territory. *Bur. Miner. Resour. Aust. Bull.* 16.

NOAKES, L. C., ÖPIK, A. A., and CRESPIN, IRENE, 1952—Bonaparte Gulf Basin, northwestern Australia: a stratigraphical summary with special reference to the Gondwana System. *Cong. int. géol., 19ième Sess. Alger: Symposium sur les séries de Gondwana,* 91-106.

PLAYFORD, P. E., and LOWRY, D. C., 1967—Devonian reef complexes of the Canning Basin, Western Australia. *Geol. Surv. W. Aust. Bull.* 118.

PLAYFORD, P. E., VEEVERS, J. J., and ROBERTS, J., 1966—Upper Devonian and possible Lower Carboniferous reef complexes in the Bonaparte Gulf Basin. *Aust. J. Sci,* 28(11), 436-7.

REEVES, F., 1951—Australian oil possibilities. *Bull. Amer. Ass. Petrol. Geol.,* 35, 2479-525.

ROBERTS, J., JONES, P. J., and DRUCE, E. C., 1967—Palaeontology and correlation of the Upper Devonian of the Bonaparte Gulf Basin, Western Australia and Northern Territory. *International Symposium on the Devonian System, Calgary, Canada* (in press).

ROBERTS, J., and VEEVERS, J. J., 1967—Carboniferous geology of the Bonaparte Gulf Basin, northwestern Australia. *6th Carb. Cong.* (in press).

ROBINSON, G. D., 1959—Measuring dipping beds. *GeoTimes,* 4(1), 8-9, 24-7.

THOMAS, G. A., 1962—The Carboniferous stratigraphy of the Bonaparte Gulf Basin. *Cong. Avanc. Et. strat. carbonif., Heerlen,* 1958, 3, 727-32.

THOMAS, G. A., 1965a—An echinoid from the Lower Carboniferous of northwest Australia. *Proc. Roy. Soc. Vic.,* N.S. 79(1), 175-8, pl. 25.

THOMAS, G. A., 1965b—*Delepinea* in the Lower Carboniferous of northwest Australia. *J. Palaeont.,* 39(1), 97-102, pl. 18A.

TRAVES, D. M., 1955—The geology of the Ord-Victoria region, northern Australia. *Bur. Miner. Resour. Aust. Bull.* 27.

VALE, K. R., and JONES, B. F., 1967—Australian offshore exploration—the sedimentary environment and its coercive influence. *Proc. World Petrol. Cong. Mexico* (in press).

VAN ANDEL, TJ. H., and VEEVERS, J. J., 1967—Morphology and sediments of the Timor Sea. *Bur. Miner. Resour. Aust. Bull.* 83.

VEEVERS, J. J., 1967a—Cartier Furrow, a major structure along the continental margin of northwestern Australia. *Nature,* 215 (5098), 265-267.

VEEVERS, J. J., 1967b—The Phanerozoic geological history of northwest Australia. *J. geol. Soc. Aust.,* 14(2), 253-272.

VEEVERS, J. J., 1968—Upper Devonian and Carboniferous sedimentology of the Bonaparte Gulf Basin. *Bur. Miner. Resour. Aust. Bull.* 109 (in press).

VEEVERS, J. J., and ROBERTS, J., 1966—Littoral talus breccia and probable beach rock from the Visean of the Bonaparte Gulf Basin. *J. geol. Soc. Aust.,* 13(2), 387-403, pls 4, 5.

VEEVERS, J. J., and ROBERTS, J., 1967—Upper Devonian geology of the Bonaparte Gulf Basin, Western Australia and Northern Territory. *Int. Symp. Devonian System, Calgary* (in press).

VEEVERS, J. J., ROBERTS, J., KAULBACK, J. A., and JONES, P. J., 1964—New observations on the Palaeozoic geology of the Ord River area, Western Australia and Northern Territory. *Aust. J. Sci.,* 26(11), 352-3.

VEEVERS, J. J., and VAN ANDEL, TJ. H., 1967—Correspondence between submarine morphology and magnetic basement of the Sahul Shelf. *Mar. Geol.,* 5, 293-298.

VEEVERS, J. J., and WELLS, A. T., 1961—The geology of the Canning Basin, Western Australia. *Bur. Miner. Resour. Aust. Bull.* 60

VOIGT, E., 1959—Die ökologische Bedeutung der Hartgründe („Hardgrounds") in der oberen Kreide. *Paläont. Zeitschr.,* 33(3), 129-47.

WADE, A., 1924—Petroleum prospects, Kimberley District of Western Australia and Northern Territory. *By authority, Melb.*

UNPUBLISHED

ALLEN, P. J., 1956—Report of the Keep River Party, 1956. *Private report number NT/KR/25 by Mines Administration Pty Ltd for Westralian Oil Ltd.*

BIGG-WITHER, A. L., 1963—Compilation and review of the geophysics of the Bonaparte Gulf Basin, 1962. *Bur. Miner. Resour. Aust. Rec.* 1963/165.

CREEVEY, K., 1966—Well completion report, Aquitaine Kulshill No. 2. *Report to Australian Aquitaine Petroleum Pty Ltd.*

DRUMMOND, J. M., 1963—Compilation and review of the geology of the Bonaparte Gulf Basin, 1962. *Bur. Miner. Resour. Aust. Rec.* 1963/133.

DUCHEMIN, A. E., and CREEVEY, K., 1966—Well completion report, Aquitaine Kulshill No. 1. *Report to Australian Aquitaine Petroleum Pty Ltd.*

GLOVER, J. J. E., RICHARDSON, L. A., and MCGILVRAY, E., 1955—Geological and geophysical report on the Keep River area, Bonaparte Gulf Basin. *Private report for Assoc. Aust. Oilfields.*

HARE, R., and ASSOCIATES (revised by G. A. THOMAS), 1961—Oil Development N.L. Well completion report. Spirit Hill Well No. 1. *Oil Development N.L. and Westralian Oil Limited.*

JACQUEMIN, M., 1966—Timor Sea aeromagnetic survey. *Private report to Australian Aquitaine Petroleum Pty Ltd.*

LE BLANC, M. C., 1964—Alliance Oil Development Australia N.L. completion report. Bonaparte Well No. 1 P.E. 127H, Western Australia. *Alliance Oil Development N.L.*

LE BLANC, M. C., 1965—Alliance Oil Development Australia N.L. completion report. Bonaparte Well No. 2 P.E. 127H, Western Australia. *Alliance Oil Development N.L.*

PETTY GEOPHYSICAL ENGINEERING COMPANY, 1964a—Reflection seismograph survey of the Surprise Creek area, W.A. *Alliance Oil Development.*
1964b—Legune seismic and gravity geophysical report. *Australian Aquitaine Petroleum Ltd.*
1965a—Skull Creek seismic geophysical report. *Australian Aquitaine Petroleum Ltd.*
1965b—Tanmurra seismic geophysical report. *Anacapa Corporation.*

REEVES, F., 1958—Report on geology and oil possibilities of the Bonaparte Gulf Basin. *Private report for Standard Vacuum Ltd.*

SMITH, E. R., 1966—Timor Sea/Joseph Bonaparte Gulf marine gravity and seismic spark array survey, northwest Australia, 1965. *Bur. Miner. Resour. Aust. Rec.* 1966/72.

UNITED GEOPHYSICAL CORPORATION, 1964—Ningbing/Burt Range seismic survey. *Alliance Oil Development.*

UTTING, E. P., 1957—Report on exploration and geology within Permit 3 Northern Territory, during 1956. *Private report to Westralian Oil Ltd.*

UTTING, E. P., 1958—Progress geological report, Permit No. 3, Bonaparte Gulf Basin. *Private report to Westralian Oil Ltd.*

APPENDIX 1

NEW GEOGRAPHICAL NAMES IN THE BONAPARTE GULF BASIN

by

J. J. Veevers and J. Roberts

Name	*Derivation of Name*	*Feature*	*Geographical Co-ordinates*
Abney Hill	From 'Abney Level', the instrument used in geologically surveying this feature	Scarp, 200 ft high, in red sandstone	15°44′S 128°44′E
Alpha Hill	From the registration letters of the helicopter (VH-AHH) which conveyed the authors to this hill	Highest point in a sandstone ridge	15°26′S 129°10′E
Burvill Point	After Mr G. H. Burvill, Department of Agriculture, Perth	Top of sandstone hill, 1 mile ESE of Ningbing Hills	15°16′S 128°40′E
Hargreaves Hills	After Mr F. Hargreaves, Manager of Carlton Hill station	Group of sandstone ridges	15°20′S 128°33′E
Jeremiah Hills	After one of the children of the Durack family	Group of limestone hills	15°26′S 128°43′E
Langfield Point	After Mr E. C. B. Langfield, the first officer-in-charge of Kimberley Research Station	W tip of Burt Range	15°48′S 128°58′E
Matheson Ridge	After Mr R. S. Matheson who, as geologist of the Geological Survey of Western Australia, jointly wrote the first scientific report on the Devonian and Carboniferous rocks of the area	Ridge of sandstone and basalt	From 15°48′S 128°58′E to 15°53′S 128°55′E
Mount Zimmermann	After Dr M. Zimmermann, who in 1963 was leader of the Australian Aquitaine Petroleum party that worked in this area	Conspicuous peak of sandstone and conglomerate in W part of Burt Range	15°46′S 128°57′E
Ningbing Range	After Ningbing homestead	Dissected range of limestone	From 15°20′S 128°36′E to 14°57′S 128°35′E
Öpik Hill	After Dr A. A. Öpik, who in 1949 made several geological discoveries in the area	Sandstone peak in the headwaters of Tanmurra Ck	15°03′S 128°36′E
Siggins Spring	After Mr A. Siggins, surveyor, PWD, Kununurra	Freshwater spring in limestone, at head of Mistake Ck	15°17′S 128°36′E
Sorby Hills	After H. C. Sorby, the eminent carbonate petrologist	Group of limestone hills at NE tip of Pincombe Range	15°28′S 128°43′E
Utting Gap	After Mr E. P. Utting, who geologically pioneered the Ningbing Range	Gap between Ningbing Range and sandstone	14°58′S 128°36′E

AIR-PHOTOGRAPH CO-ORDINATES

Feature	*Sheet*	*Run*	*No.*	*Quadrant*	*X*	*Y*	*Diagonal*
Abney Hill	CG	12	5047	C	3.50	0.20	3.60
Alpha Hill	AU	7	5076	B	1.75	0.70	1.90
Burvill Point	CG	4	5165	B	1.90	0.80	2.10
Hargreaves Hill*	CG	5	5181	A	2.50	2.40	3.50
,, ,,	CG	5	5181	C	3.20	3.00	4.35
Langfield Point	CG	12	5053	D	2.75	3.80	4.70
Matheson Ridge*	CG	14	5139	C	2.75	4.30	5.10
,, ,,	CG	14	5139	D	1.10	1.45	1.80
Mount Zimmermann	CG	12	5053	D	1.55	4.20	4.45
Ningbing Range*	CG	5	5179	A	1.90	1.50	2.45
,, ,,	MB	14	5080	D	1.90	2.10	2.80
Öpik Hill	CG	2	5077	A	1.80	0.25	1.85
Siggins Springs	CG	5	5179	B	0.10	1.35	1.35
Sorby Hills*	CG	8	5109	D	1.50	1.65	2.20
,, ,,	CG	8	5109	C	1.00	1.40	1.75
Jeremiah Hills*	CG	7	5027	C	0.70	0.65	0.95
,, ,,	CG	7	5027	C	4.00	0.10	4.00
Utting Gap	MB	15	5010	C	3.80	1.25	4.00

NOTE:

CG — Cambridge Gulf 1:250,000 Sheet area
MB — Medusa Banks 1:250,000 Sheet area
AU — Auvergne 1:250,000 Sheet area
* — Co-ordinates of extremities of feature

APPENDIX 2

STRUCTURE REFLECTED BY JOINT PATTERNS IN THE BONAPARTE GULF BASIN

by

J. J. Veevers and C. E. Maffi

ABSTRACT

Air-photograph interpretation shows the cross-bedded quartz sandstone in the Upper Devonian and Carboniferous sequence of the Bonaparte Gulf basin is jointed in patterns that reflect local structures, chiefly faults. One of the areas studied (Ragged Range) contains an anomalous joint pattern which possibly indicates a concealed structure.

The air-photographs of many areas of outcropping Upper Devonian and Carboniferous sandstones in the Bonaparte Gulf Basin show abundant linear features. Most of them are furrows or ravines cut along outcropping joints in cross-bedded quartz sandstone. The deep etching of intersecting sets of joints leads to the isolation of blocks of sandstone in characteristic shapes likened to beehives, castles, or ruins. Outcrops of this kind are common in parts of the Ragged Range Conglomerate Member, Kellys Knob Sandstone Member, and Cecil Sandstone Member of the Cockatoo Formation, the Point Spring Sandstone, and the Border Creek Formation. From field observations, most of the joints are known to have a steep or vertical dip, so that their outcrop trace is not seriously affected by the low dips, commonly 5° or less, of the rocks in which they occur in the areas studied, which are shown on Figure 1. These areas contain fairly large continuous outcrops of jointed quartz sandstone, so that the various joint sets are readily identified within each area.

The other formations of quartz sandstone in the Upper Devonian and Carboniferous sequence consist of flat-bedded quartz sandstone in which joints are rare. This contrast is best seen in the Point Spring Sandstone (Pl. 1), the only formation which consists of interbedded cross-bedded quartz sandstone (with joints) and flat-bedded sandstone (virtually without joints). The only obvious difference between these two types of sandstone is in their bedding (Veevers, Bull. 109 in press), so that the restriction of joints to the cross-bedded sandstone is presumably influenced by a factor or a combination of factors related to the cross-bedding. Possibly the looser packing of the sand grains and the numerous planes of weakness in the cross-bedded sandstone make it favourable for the development of joints.

Methods

Linears were traced from the air-photographs on to translucent overlays, which were then compiled over a controlled base. Air-photographs at a scale of 1:16,000 were available for the Weaber Range and Spirit Hill, and at a scale of 1:50,000 for the other areas. Each area was subdivided into squares along a grid: the Weaber Range and Spirit Hill into ½-mile squares, and the other areas into 1-mile squares. Parallel and continuous linears were grouped into sets by inspection, and the length and azimuth of individual linears were listed according to set and square. Resultant azimuths of each set within each square were computed using Curray's (1956) method,* and computations were carried out on a Control Data 3600 computer with a programme written by T. Quinlan. Resultant azimuths, the vector magnitude or degree of preferred orientation, and the total length of the

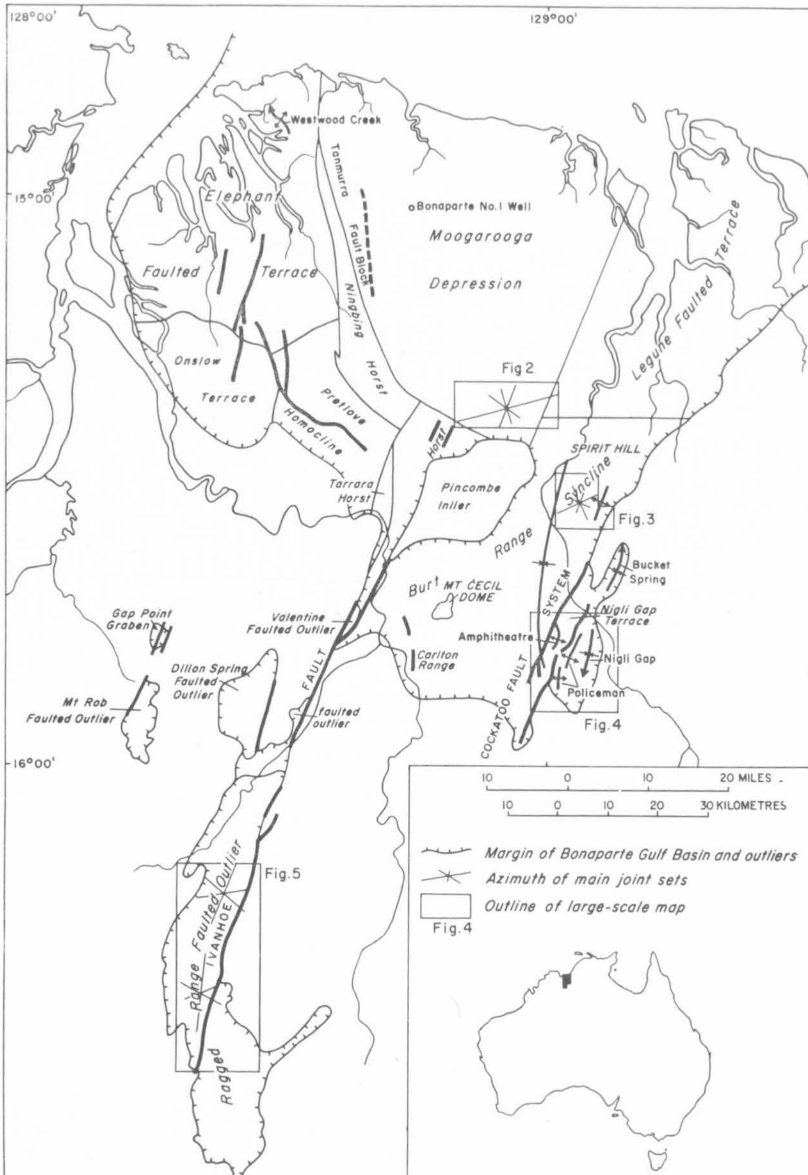


Figure 1. Structural map of the Bonaparte Gulf Basin, showing areas of study and their summarized joint patterns. For the sake of clarity, the joint patterns in inset Figure 4 are not shown

---

* A sign is misprinted in this paper. In the second group of formulae on p. 119, read—

$$r = \sqrt{(\Sigma n \sin 2\theta)^2 + (\Sigma n \cos 2\theta)^2}$$

set were computed for each set in each square. The azimuths of all but a few sets were statistically significant, the probability of the resultant of all but a few sets being less than 10^{-4}. In effect, the resultant azimuths constitute rose diagrams that merely summarize the distribution of the various joint sets within each square. The resultant azimuths were plotted proportional to their length on the maps, and generalized trends of linears were interpolated on the maps of the Weaber Range, Spirit Hill, and Nigli Gap areas, where the linears are visibly continuous.

Weaber Range (Fig. 2)

The main outcropping rocks of the Weaber Range are the Point Spring Sandstone and the overlying Border Creek Formation, which are separated by an erosional disconformity. Both formations contain numerous thick bodies of jointed cross-bedded quartz sandstone. Despite the disconformity, both formations have the same pattern of linears, and for the sake of clarity the formations are not differentiated on the map.

Four sets were recognized:

Set 1, with east-northeast trend, normal to Set 2, with north-northwest trend; Set 3, with northwest trend, normal to Set 4, with northeast trend.

All these sets are expressed by the same kind of linear, which is individually narrow and short, except in the central part of the area, which contains widely-spaced linears up to a mile long. The long linears lie parallel to the sets of short linears.

Set 1 linears are dominant, and are found in the entire mapped area. Near Point Spring, Set 1 parallels the strike, but elsewhere it is independent of the strike. North and west of Point Spring, all but a few of the linears belong to Set 1. Set 2 is secondary, and is found only in the area 4 miles northeast of Point Spring, where it parallels faults of short throw, and in the eastern part of the Weaber Range. Sets 3 and 4 are subordinate. Set 4 is best expressed north-northeast of Point Spring, where it parallels a system of faults. All the faults shown in Figure 2 have small throws, and they may be loosely grouped with joints.

The Weaber Range lies north of the Precambrian Pincombe Inlier along the southern margin of the Moogarooga Depression (Fig. 1). The dominant joint trend (Set 1) is normal to the elongation of the depression, and Set 2 is parallel to it. The subordinate trends (Sets 3 and 4) parallel the southwest and southeast margins of the depression.

The same pattern of joints is found in the Point Spring Sandstone (Lower Carboniferous) and Border Creek Formation (Upper Carboniferous), which are separated by an erosional disconformity, indicating that the joints probably originated after the deposition of the Border Creek Formation; and since the joint sets are related geometrically to the axis and margins of the Moogarooga Depression, the joints probably resulted from the movement, mainly along faults, that produced the Moogarooga Depression, which Veevers & Roberts date as probably Upper Permian.

Spirit Hill (Fig. 3)

The Border Creek Formation crops out in the western part of Spirit Hill, and consists of jointed conglomeratic quartz sandstone. Like its namesake in

Plate 1. Part of air-photograph No. 5,176, Run 5 of Cambridge Gulf sheet, nominal scale 1:50,000—Part of the Weaber Range, showing the alternation of cross-bedded sandstone (jointed) and flat-bedded sandstone (without joints)

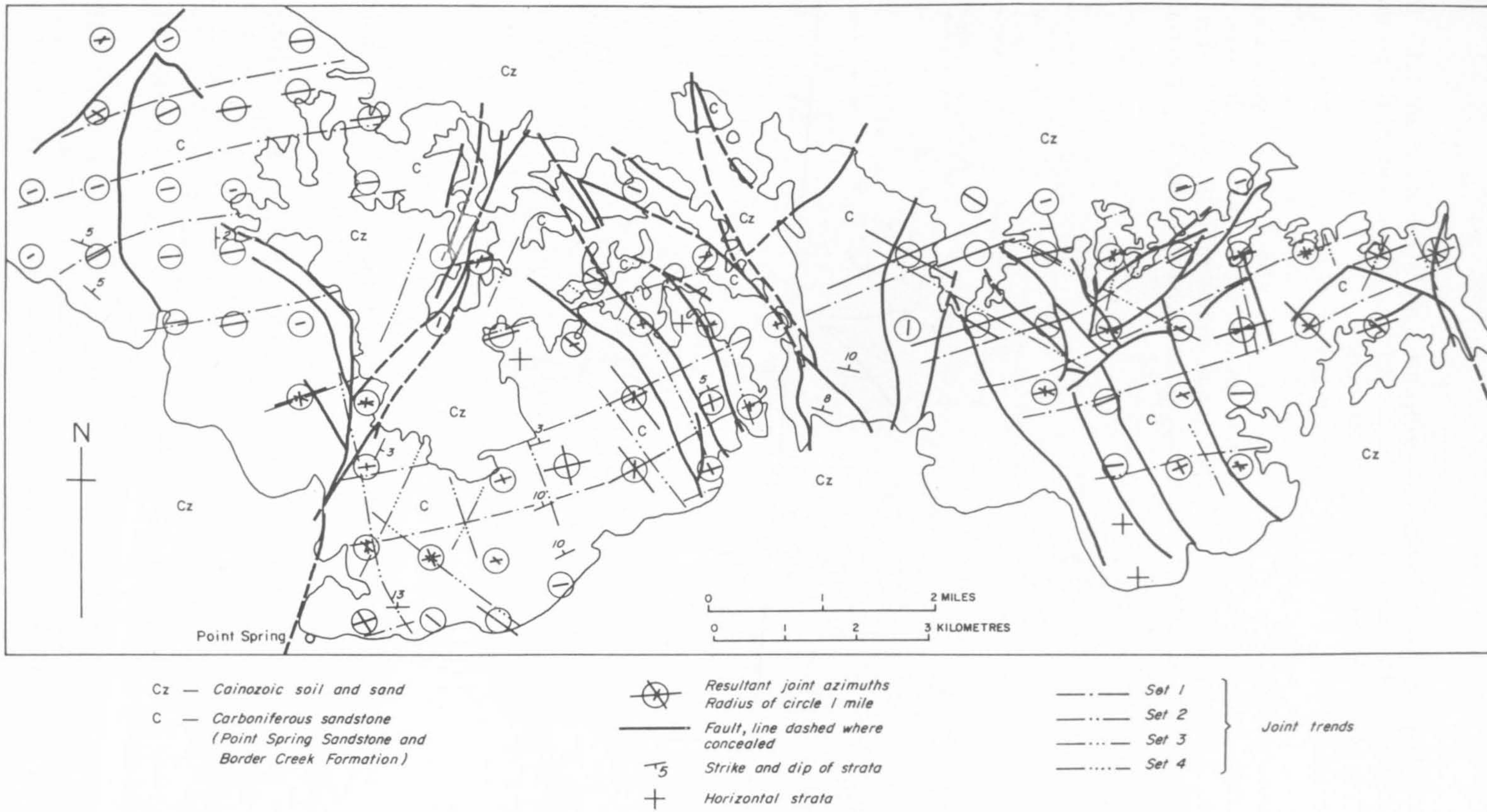


Figure 2. The Weaber Range, showing joint patterns and faults

the Weaber Range, Set 1 trends east-northeast, and is the dominant set. It is normal to Set 2. The other sets are minor: Set 3 is known only in the northern part of Spirit Hill, and Set 4 in the southern part.

The jointed area lies on the limb between the Spirit Hill Anticline on the east and the Burt Range Syncline on the west. The dominant trend (Set 1) and the secondary trend (Set 2) intersect at an angle whose bisector parallels the axes of these folds; one of the subordinate trends (Set 3) parallels the axes, the other (Set 4) is normal to them. These relationships probably indicate that the folds and the joints originated at the same time, probably in the Upper Permian.

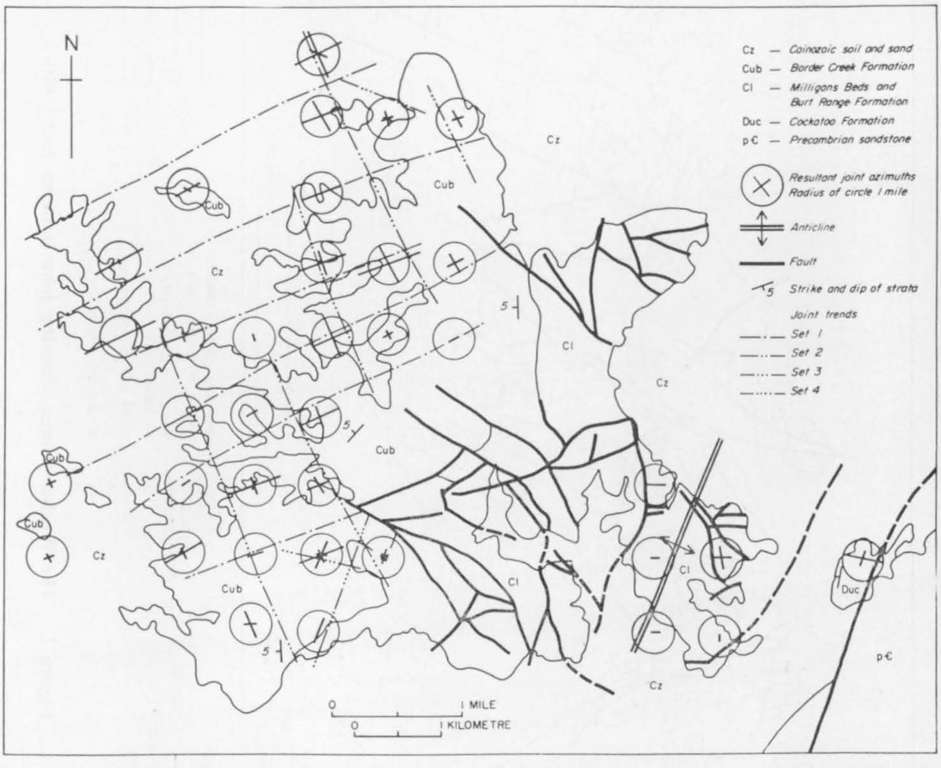


Figure 3. Spirit Hill, showing joint patterns, faults, and the axis of the Spirit Hill Anticline

Nigli Gap (Fig. 4)

The jointed sandstone in this area belongs to the Kellys Knob Sandstone Member of the Cockatoo Formation. Two curved systems of paired normal sets were found. Set 1 changes trend from north to north-northeast, and this change is followed by Set 2, which remains at right-angles to Set 1. Likewise, Set 3 changes trend from north to north-northwest, and this change too is followed by the normal Set 4.

This area lies within the Cockatoo Fault system, and the joint patterns reflect the complexity of structure brought about by the interference of many direct fault movements. In contrast to the other areas studied, no simple interpretation is possible.

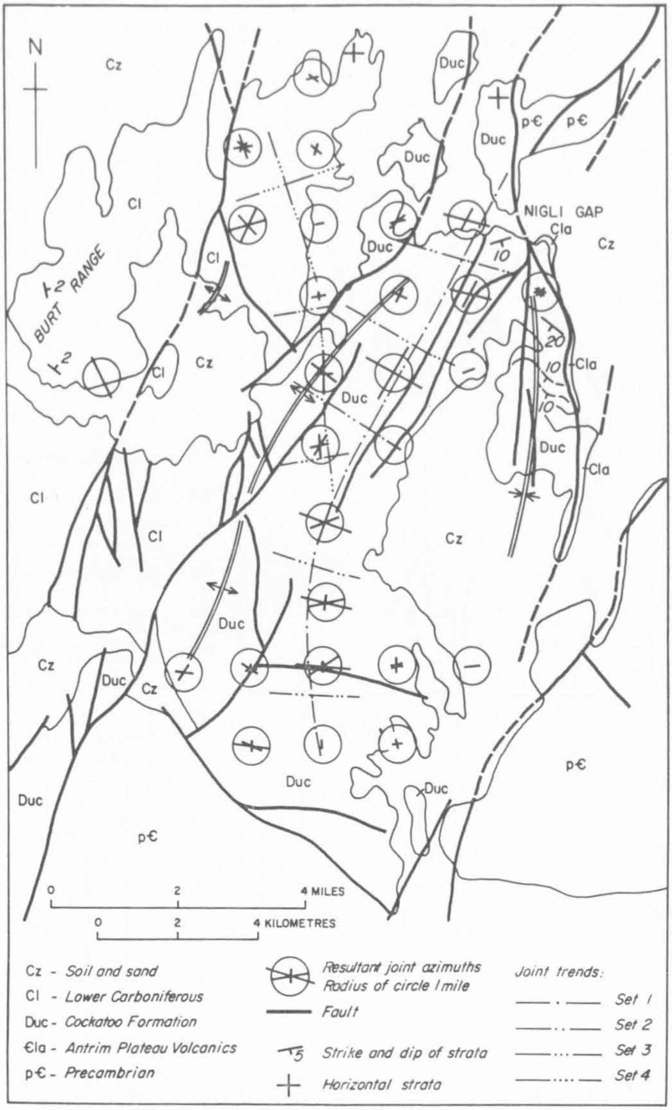


Figure 4. The Nigli Gap area, showing joint patterns, faults, and folds in part of the Cockatoo Fault system

Ragged Range (Fig. 5)

Two areas of the Ragged Range Conglomerate Member and probable Cecil Sandstone Member of the Cockatoo Formation in the Ragged Range contain abundant linears. In both areas, the dominant north to north-northeasterly set follows the curve of the Ivanhoe Fault system. In the northern part of the Ragged Range, major sets with east-northeast and northwest trends are distributed symmetrically about the set parallel to the fault, and possibly indicate concealed west-northwest cross structures continuous to the east with the outcropping fault in the Precambrian rocks.

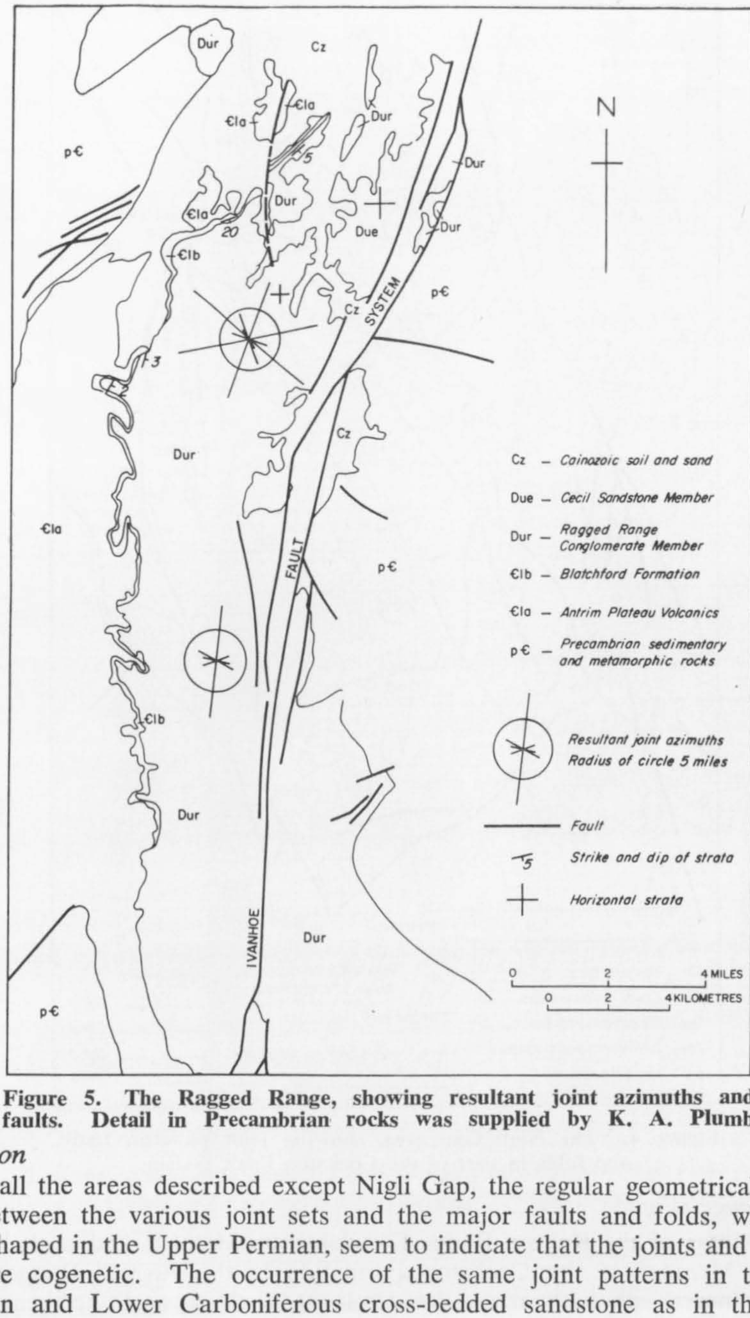


Figure 5. The Ragged Range, showing resultant joint azimuths and faults. Detail in Precambrian rocks was supplied by K. A. Plumb

Discussion

In all the areas described except Nigli Gap, the regular geometrical relationships between the various joint sets and the major faults and folds, which were finally shaped in the Upper Permian, seem to indicate that the joints and the structures are cogenetic. The occurrence of the same joint patterns in the Upper Devonian and Lower Carboniferous cross-bedded sandstone as in the disconformably overlying Upper Carboniferous Border Creek Formation shows that all the joints are younger than Upper Carboniferous. The more complex joint pattern in the Nigli Gap area reflects the complex structure within the Cockatoo Fault system. A concealed cross structure in the northern Ragged Range is indicated by two joint sets that intersect the dominant joint sets at high angles.

We hope that this outline of the relationships of the joint patterns in the sandstones of the Bonaparte Gulf Basin, as seen in air-photographs, will show the promise of this area for more refined studies of joints.

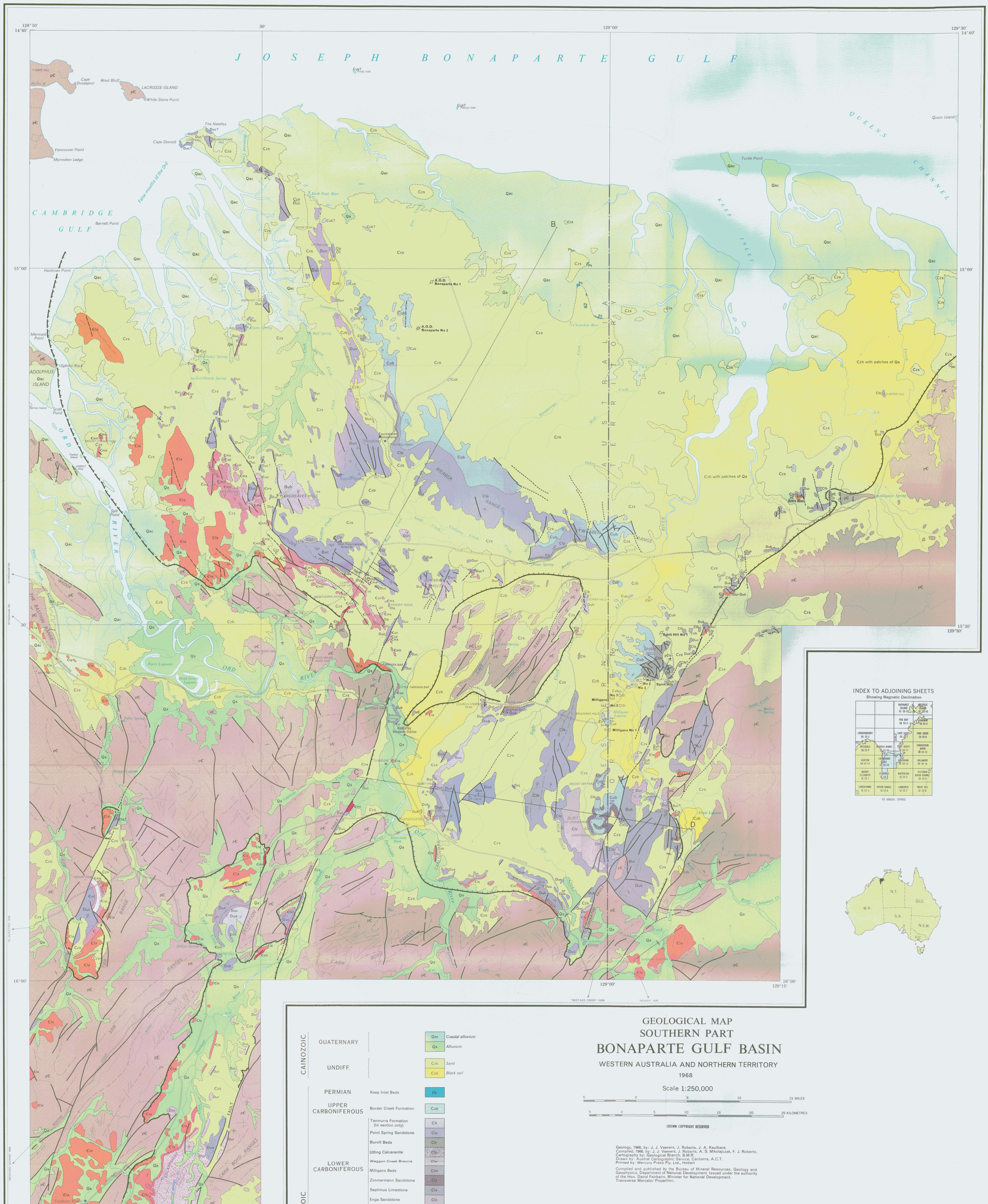
Acknowledgments

We thank our Bureau colleagues T. Quinlan for preparing a computer programme and K. A. Plumb for supplying details of structure in the Precambrian rocks in the Ragged Range area. Dr K. Burns, Macquarie University, and Dr K. H. R. Moelle, University of Newcastle, provided invaluable discussion.

REFERENCES

CURRAY, J. R., 1956—The analysis of two-dimensional orientation data. *J. Geol.*, 64(2), 117-131.

VEEVERS, J. J., in press—Sedimentology of the Upper Devonian and Carboniferous platform sequence of the Bonaparte Gulf Basin. *Bur. Miner. Resour. Aust. Bull.* 109.



GEOLOGICAL MAP
SOUTHERN PART
BONAPARTE GULF BASIN

WESTERN AUSTRALIA AND NORTHERN TERRITORY

1968

Scale 1:250,000

5 0 5 10 15 MILES

5 0 5 10 15 20 25 KILOMETRES

Geology, 1966, by: J. J. Veevers, J. Roberts, J. A. Kaulback.
Compiled, 1966, by: J. J. Veevers, J. Roberts, A. S. Mikolajczak, F. J. Roberts.
Cartography by: Geological Branch, B.M.R.
Drawn by: Austral Cartographic Service, Canberra, A.C.T.
Printed by: Mercury Press Pty. Ltd., Hobart

Compiled and published by the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development. Issued under the authority of the Hon. David Fairbairn, Minister for National Development.
Transverse Mercator Projection.

CAINOZOIC

QUATERNARY
- Qac — Coastal alluvium
- Qa — Alluvium

UNDIFF.
- Czs — Sand
- Czb — Black soil

PALAEOZOIC

PERMIAN
- Keep Inlet Beds — Pk

UPPER CARBONIFEROUS
- Border Creek Formation — Cub

LOWER CARBONIFEROUS
- Tanmurra Formation (In section only) — Clt
- Point Spring Sandstone — Clp
- Burvill Beds — Clr
- Utting Calcarenite — Clu
- Waggon Creek Breccia — Clw
- Milligans Beds — Clm
- Zimmermann Sandstone — Clz
- Septimus Limestone — Cls
- Enga Sandstone — Cle
- Burt Range Formation — Clb

UPPER DEVONIAN TO LOWER CARBONIFEROUS
- Bonaparte Beds (In section only) — D-Cb

UPPER DEVONIAN
- Buttons Beds — Dub
- Ningbing Limestone — Dun
- Cockatoo Formation
- Jeremiah Member
- Cecil Sandstone Member
- Abney Sandstone Member
- Kununurra Member
- Kellys Knob Sandstone Member
- Westwood Member
- Hargreaves Member
- Ragged Range Conglomerate Member

PALAEOZOIC

LOWER ORDOVICIAN
- Pander Greensand — Olp

UPPER CAMBRIAN
- Clark Sandstone — €uc
- Pretlove Sandstone — €up

MIDDLE CAMBRIAN
- Skewthorpe Formation — €ms
- Hart Spring Sandstone — €mh
- Tarrara Formation — €mt

LOWER CAMBRIAN
- Blatchford Formation — €lb
- Antrim Plateau Volcanics — €la

CAMBRIAN
- Undifferentiated — €

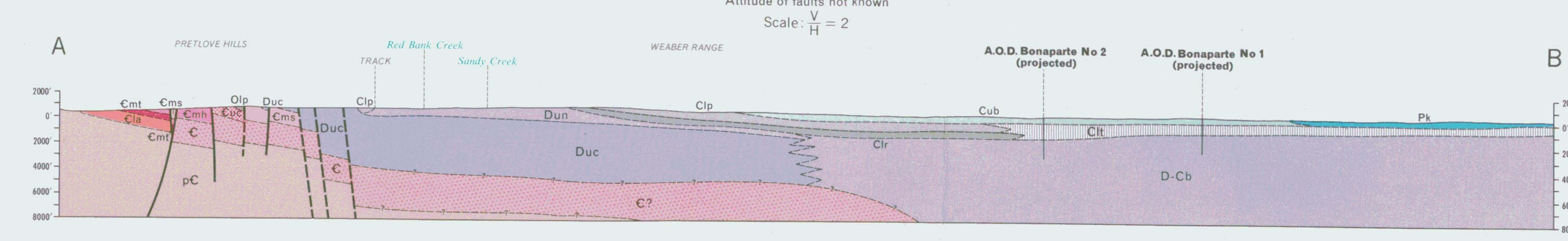
PRECAMBRIAN
- Undifferentiated — p€

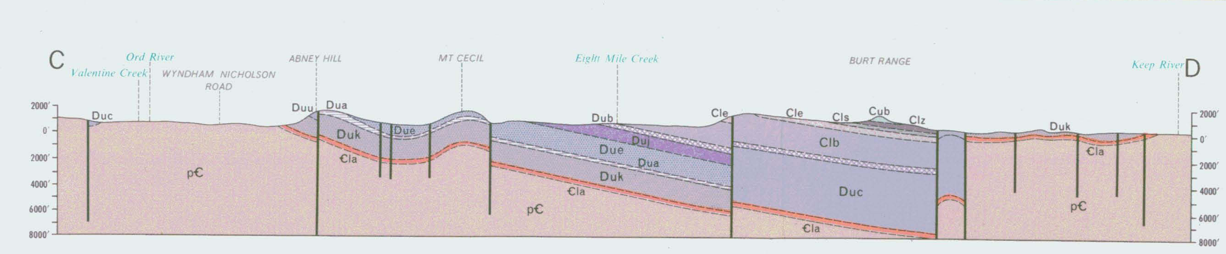
Geological boundary
Anticline, showing plunge
Syncline
Fault
Where location of boundaries, folds and faults is approximate, line is broken; where inferred, queried; where concealed, boundaries and folds are dotted, faults are shown by short dashes.
Strike and dip of strata
Prevailing strike and dip of strata
Horizontal strata
Dip < 15°
Trend lines } air-photo interpretation
Joint Pattern } air-photo interpretation
Oil exploration well: St — stratigraphic hole
Oil exploration well: abandoned, dry
Oil exploration well with show of gas: abandoned

Mine
Bore
Windpump
Waterhole
Spring
Highway
Road
Vehicle track
Airport
Landing ground
Homestead
State boundary
Margin of Bonaparte Gulf Basin

Sections

Cainozoic sediments omitted from sections
Attitude of faults not known
Scale: $\frac{V}{H} = 2$





BONAPARTE GULF BASIN

Copies of this map may be obtained from the Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., or Darwin, N.T. or the Geological Survey of Western Australia, Perth