BMR Bulletin

200

THE GEOLOGY OF THE FAIRFIELD GROUP, CANNING BASIN, WESTERN AUSTRALIA

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

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AUSTRALIAN GOVERNMENT PUBLISHING SERVICE
CANBERRA 1979

DEPARTMENT OF NATIONAL DEVELOPMENT

MINISTER: THE HON. K. E. NEWMAN, M.P.

SECRETARY: A. J. WOODS

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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ABSTRACT

The geology of the latest Devonian and earliest Carboniferous Fairfield Group is described. Outcrop is confined to the northern margin of the Canning Basin on the Lennard Shelf, and the rocks are divided into three formations, the Gumhole Formation, Yellow Drum Sandstone and Laurel Formation.

The Gumhole Formation (latest Famennian) consists of limestone, siltstone, shale, and sandstone, with minor dolomite. It contains a diverse biota of brachiopods, bryozoans, molluscs, ostracods, conodonts, corals, and spores.

The Yellow Drum Sandstone, which straddles the Devonian-Carboniferous boundary, consists of calcareous sandstone, silty dolomite, and dolomitic siltstone with minor shale and limestone. The biota is impoverished relative to the enclosing units — apart from the microflora, which is relatively diverse and diagnostic.

The Laurel Formation (early Tournaisian) consists of limestone, shale, siltstone, sandstone, and minor dolomite. The biota is rich and varied, and includes algae, brachiopods, bryozoans, conodonts, corals, fish, molluscs, ostracods and spores.

The Fairfield Group represents a sequence deposited during an initial transgression (Gumhole Formation), a regression (Gumhole Formation and Yellow Drum Sandstone), and a subsequent transgression (Yellow Drum Sandstone and Laurel Formation).

The Gumhole Formation represents deposition in a platform environment with shoals, bioherms and subtidal drainage channels. The Yellow Drum Sandstone represents deposition in a supratidal environment with mudflats which were occasionally inundated by the sea. During the regressive phase this facies migrated southward across the basin.

The subsequent transgression was responsible for the deposition of the Laurel Formation, which represents deposition on a platform where conditions varied from open marine to lagoonal, and included restricted conditions and shoal and intershoal areas.

Economically the Group is of interest because of minor oil and gas shows within it; the possibility of the porous and permeable Yellow Drum Sandstone being a good reservoir rock; and the shales and siltstones of the Laurel Formation acting as an impervious cap.

Published for the Bureau of Mineral Resources, Geology and Geophysics by The Australian Government Publishing Service

ISBN 0 642 03634 9

DATE OF ISSUE 30 AUG 1979

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INTRODUCTION

The Canning Basin, which covers some 450,000 km², is the largest sedimentary basin in Western Australia. The earliest Palaeozoic rocks are widespread marine Ordovician limestone, shale and sandstone up to 3260 m thick which unconformably overlie Precambrian metamorphic and sedimentary rocks. Overlying the Ordovician are Devonian rocks, consisting of evaporites and redbeds (probably Early and Middle Devonian) confined to the centre of the basin, and extensive Late Devonian reef carbonates on the northerly and, perhaps, the southerly margin, together with associated shale and sandstone in the centre of the basin. The Devonian sediments are overlain by Carboniferous, Permian, Mesozoic and Cainozoic sediments.

During the Late Devonian and Carboniferous, sedimentation was virtually confined to the northern half of the Basin: on the Lennard Shelf, in the Fitzroy Trough, and on the Jurgurra Terrace (Fig. 2). The trough contains up to 6000 m of Carboniferous rocks.

The Upper Devonian — Lower Carboniferous platform sediments consist of alternating beds of limestone, shale, sandstone, and marl. Generally, they postdate the Devonian reef-complex (Playford & Lowry, 1966) and are poorly exposed; consequently they have received less geological attention than the well-exposed reef carbonates. Previous work has resulted in differing interpretations of the formal stratigraphy; including different nomenclatures for the same rock bodies. The presence of an unconformity has also been questioned.

During May — August 1972 a joint Bureau of Mineral Resources (BMR) — Western Australian Geological Survey (WAGS) Field Party carried out detailed fieldwork in the vicinity of Fitzroy Crossing, Western Australia. Comprehensive collections of petrographic, palaeontological, and geochemical samples were made from the Upper Devonian and Lower Carboniferous to increase the understanding of the sequence.

The area of outcrop is situated on the northern margin of the Canning Basin in the Kimberley Division of Western Australia (Fig. 1). Detailed fieldwork was concentrated in three areas; a narrow belt (up to 10 km wide) extending along the southwest face of the Napier and Oscar Ranges from Station Creek in the northwest to Fitzroy Crossing in the southeast, a distance of about 160 km; the Horseshoe and Burramundi Ranges, 65 km east of Fitzroy Crossing; and the Red Bluffs area, 135 km southeast of Fitzroy

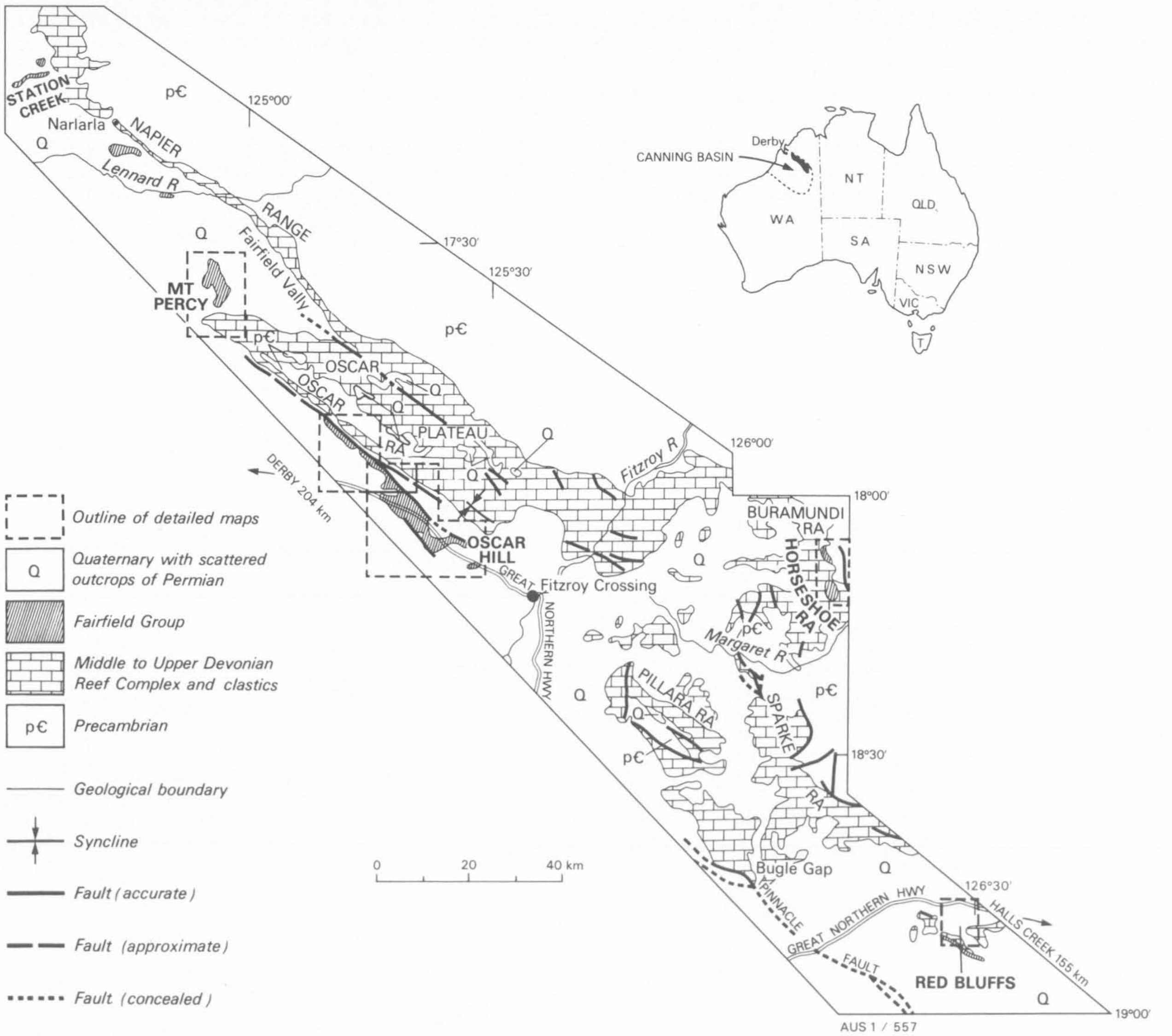

Figure 1. Locality map, Fairfield Group.

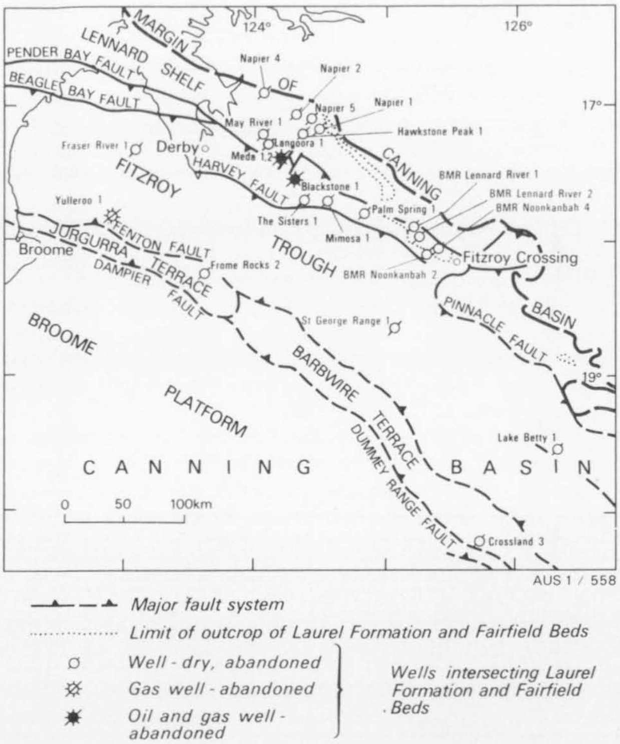

Figure 2. Structural map, northern Canning Basin.

Crossing (Figs. 4-8). The area is traversed by the Great Northern Highway (Derby — Fitzroy Crossing — Halls Creek) and the Derby — Mount House road. Access to the outcrop area is generally good and is by means of station tracks. Access to the exposures in the Horseshoe Range is, however, difficult and most material was collected during a helicopter traverse. As well as station airstrips, commercial airports are situated at Derby and Fitzroy Crossing.

Methods of Study

The outcrop areas were mapped on air photographs at a scale of 1:80,000. Comprehensive sections were measured and samples for petrological, palaeontological, and geochemical studies were collected at intervals of 1.5 m, or more, depending on outcrop. Thirty sections were measured, from which some 500 samples were collected.

Detailed reports have been published or are in press dealing with the distinction of limestones in the sequence (Radke, 1976), the conodonts (Nicoll & Druce, in prep.), and geochemistry (Druce & Radke, 1977).

In addition to surface sampling, three holes were drilled to provide information on the sequence between the oldest known Carboniferous rocks and the subsurface equivalents of nearby outcropping Devonian rocks. The holes (BMR Noonkanbah 4; BMR Lennard River 1, 2) were continuously cored to total depth using a Mayhew 1000 rig of the Petroleum Technology Section (BMR). The cores were quartered; one quarter is stored at the BMR Core and Cuttings Laboratory, Fyshwick, ACT; one quarter is held by the Geological Survey of Western Australia, Perth; the remainder has been used for palaeontological, petrological and geochemical analysis. All core was photographed in colour and prints are held by BMR, the Geological Survey of Western Australia, and West Australian Petroleum, Perth. S.P., gamma-ray, and resistivity logs were run on all holes (Druce & Radke, 1973). In this bulletin B.M. Radke is responsible for the petrology and facies interpretations.

Acknowledgements

During the field program assistance was given by Dr. R.S. Nicoll and Messrs A. Adams, J. Clark, D. Felsch and J. Gorter; A.T. Wilson was in charge of the field laboratory. Discussions on the geology of the area have been held with P.J. Jones (Palaeontology Section, BMR), D.J. Forman, J. Rasidi and J. Gorter (former Basin Studies Group, BMR),

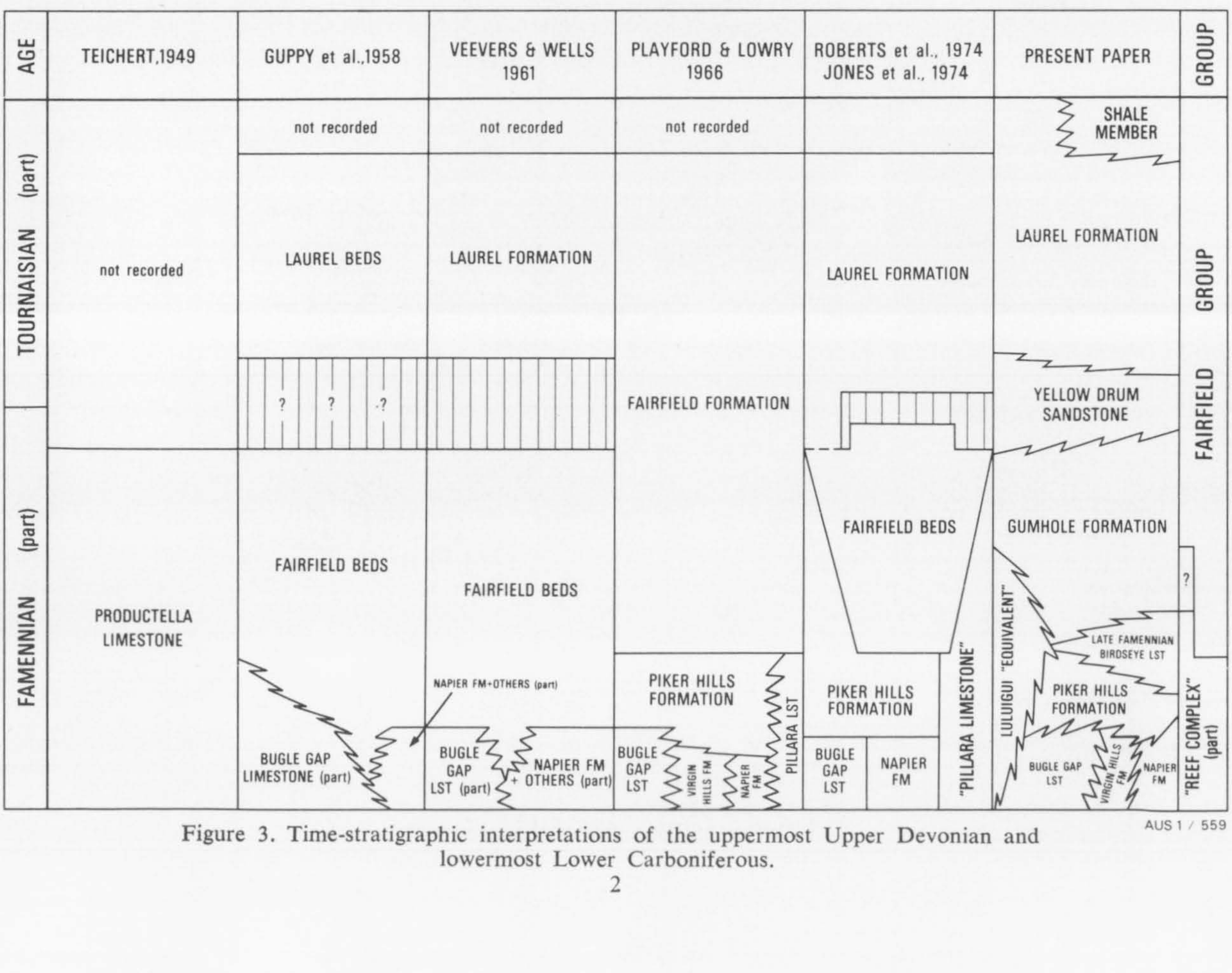

Figure 3. Time-stratigraphic interpretations of the uppermost Upper Devonian and lowermost Lower Carboniferous.

and P.J. Hawkins (Queensland Geological Survey, formerly BMR). We have received close co-operation from colleagues at the Geological Survey of Western Australia including P.E. Playford, A.C. Cockbain and E. van der Graff. The subsurface geology was discussed with geologists of WAPET, including M. Johnstone, R.A. McTavish, W. Witt, D. Lyons and A. Nott.

We are grateful to P.J. Jones, A.R. Jensen and J. Truswell for editorial comments and considerable help during the preparation of this bulletin; however, the views and opinions expressed are entirely our own.

PREVIOUS INVESTIGATIONS

The Fairfield Group comprises three formations, the Gumhole Formation, the Yellow Drum Sandstone, and the Laurel Formation. The sediments which comprise the group have been studied since the 1940's, usually as part of a larger study of the stratigraphy of the region. The development of stratigraphic interpretations of the uppermost Devonian and lowest Carboniferous platform carbonate sediments is presented in Figure 3.

STRATIGRAPHY

Until the 1930's most outcropping Devonian rocks were considered to be of Carboniferous age; eventually, goniatite (Delepine, 1935) and coral (Hill, 1936) determinations demonstrated that they are Devonian, mainly Frasnian and early Famennian.

The presence of late Famennian rocks was not recognized until 1949, when Teichert published some observations on the stratigraphy and palaeontology of the outcrops between Bugle Gap and the Oscar Range (Fig. 1). All but one of these localities are within the reef-complex; the exception is his locality No. 2, "a hill south of Oscar Homestead" now known as Oscar Hill (our locality WCB 002). Rocks of undoubted Carboniferous age were not discovered until 1953.

Teichert's work was undertaken in conjunction with geologists of Caltex (Australia) Exploration Pty. Ltd; his reports (1943, 1947, 1949) are the only published papers concerning geological field work undertaken in the 1940's. However in an unpublished report to Caltex, Kraus (1942) referred to the rocks exposed in the Fairfield Valley, especially in the Mount Percy area, and to the southwest of the Oscar Range, as the "Fairfield marl".

Rocks now recognized as belonging to the Fairfield Group were included by Teichert in his *'Productella'* limestone (1943, p. 78).

The limestone was named for the brachiopod *Spinulicosta 'Avonia' proteus* (Veevers, 1961) which was referred to *Productella* by Teichert. He recognized a *Productella* zone with a characteristic fauna of brachiopods, together with corals, pelecypods, gastropods, nautiloids and an ammonoid. All strata of the *Productella* zone were referred to the *Productella* limestone following Teichert's own rules (1949, p. 5). The main section of the *Productella* limestone is at the southwest end of Needle Eye Rocks, referred to S-Hill (Teichert's locality 27, 1949, p. 53). This was supplemented by sections in the immediate area, west to Mount Pierre and east to Pinbilly Hills (Tinbilly in Teichert's report). Teichert (1949, p. 6) gives the distribution as Oscar Range (locality 2 = Oscar Hill) in the northwest, to Mount Pierre, and probably Rough Range, in the southeast. The main outcrop areas include Fossil Downs Homestead, Fossil Hill, Needle Eye Rocks and Pinbilly Hills. The unit consists of well bedded limestone, crinoidal limestone, and limestone conglomerate with a few stromatoporoid reefs. No composite thickness was estimated but the S-Hill locality exposed 60 m, and Teichert (1949, p. 28) felt that the approximate thickness was 61 m. The *Productella* limestone overlies massive limestones in the northwest and red goniatite beds in the southeast (Teichert, 1949, p. 28); the transition between the two underlying facies is not seen. No overlying units were observed by Teichert, although he felt that Fontainebleau sandstone and conglomerate layers at Tinbilly Spring (sic) could belong to the basal Permian, and that the Devonian section ended in the vicinity of this outcrop. The abundant fauna of the *Productella* limestone is dominated by brachiopods; other groups, including poorly preserved ammonoids, are present. Teichert gave the age as doIV (in German Late Devonian zonal terms) (1943, p. 90) but noted that if a specimen questionably referred to *Laevigites* was representative of that genus then part, at least, could be doV (1949, p. 24).

The fieldwork carried out by Caltex, Vacuum Oil, and Freney Kimberley Oil Co., and the interpretation of some of the Devonian carbonates as a reef complex by Wade (1936, unpubl.), and Teichert (1949), led to an agreement between the Australian Commonwealth and the State of Western Australia to conduct geological surveys on the Lennard Shelf and the Fitzroy Trough of the Canning Basin.

Fieldwork commenced in 1948, and at the completion of the survey several maps and reports were published (Guppy *et al.*, 1958; Veevers & Wells, 1961). During this survey undoubted Carboniferous rocks were recognized for the first time. A small fossil collection made in 1953 suggested the presence of Carboniferous strata, and this was confirmed during subsequent fieldwork (Thomas, 1957). The results of the overall survey were published by Guppy *et al.* (1958), who recognised a change in environmental conditions at the Napier-Fairfield boundary. The Napier Formation is the youngest part of the reef complex; the post-Napier sequence was divided into the Fairfield Beds (Devonian) and the Laurel Beds (Carboniferous) (see below). They also recognized the *Productella* zone to the southeast in the Bugle Gap area, in strata referred to the Bugle Gap Limestone, and to the northwest in the Oscar Range area in strata referred to the Fairfield Beds. This appears to contradict Veevers' & Wells' assertion (1961, p. 42) that Guppy *et al.*, considered the *Productella* limestone to be synonymous with the Fairfield Beds.

In 1959 Veevers placed specimens of *Productella* in a new species, *Avonia proteus*, (now referred to *Spinulicosta 'Avonia' proteus*) and recognized an *Avonia proteus* zone in the latest Devonian synonymous with Teichert's *Productella* zone. Veevers noted that the Fairfield Beds were confined to the *proteus* zone but the converse was not true. In fact Veevers records the *proteus* zone from the uppermost Bugle Gap Limestone and the Geikie, Fossil Downs, Oscar, and Napier Formations, which are now all placed in the Napier Formation (*sensu* Playford & Lowry, 1966, p.65). Some of the outcrops referred to the *Productella* limestone by Teichert and subsequently to the Fairfield Beds by Veevers (1959) are now known to belong to the Piker Hills Formation (Mt Pierre and S-Hill). This formation includes most of the outcrops of the Fossil Downs Formation (*sensu* Guppy *et al.*, 1958) in the vicinity of Needle Eye Rocks, Fossil Hill, and west of the Burramundi-Horseshoe Range. Of the original *Productella* limestone localities listed by Teichert only one, Oscar Hill (Locality 2), is part of the post-reef sequence, although, as Veevers points out, all known exposures of the Fairfield

Beds (*sensu* Guppy *et al.*, 1958) are within the *proteus* zone and hence would, by definition, have been included within the *Productella* limestone.

The completion of the initial survey of the geology of the whole Canning Basin resulted in a review of the geology by Veevers & Wells (1961). They considered that the Fairfield Beds were, in part, the same age as the fore-reef and reef limestones, and were the basinward equivalent of the Fossil Downs, Napier, Geikie, and Oscar Formations, and the Bugle Gap Limestone. The Laurel Formation was postulated to overlie the Fairfield Beds unconformably.

In 1962 the Geological Survey of Western Australia began a detailed survey of the Devonian reef complex; the results were published by Playford & Lowry (1966). Although the main emphasis was on the reef complex they did concern themselves with sediments which they believed to have been laid down after reef growth had ceased (p. 90). They found it impracticable to map the "Laurel Formation" as a separate rock unit and could find no evidence to confirm the unconformity. They amalgamated the Laurel Formation and the Fairfield Beds into a single formation to which they gave the name Fairfield.

THE TERM 'FAIRFIELD'

The name Fairfield Beds was introduced by Thomas (1957) in delineating the Laurel Beds (see below). In July, 1958 the Stratigraphy of Western Australia by McWhae *et al.*, was published; the section dealing with the post-reef sediments of the Lennard Shelf drew heavily on information supplied by Guppy *et al.* (1958). Both McWhae *et al.*, and Guppy *et al.*, discussed the Fairfield Beds in detail and satisfied all the criteria for the formalisation of the name, and they designated a type area, the Fairfield Valley.

On the other hand the type section is situated to the south of the Burramundi Range (Locality DF2, in Veevers, 1959b) (fig. 5). Although it was some distance from the type area it was the thickest measured section; supplementary sections were measured throughout the area from south of Bugle Gap northwest to Old Napier Homestead. The unit consists of interbedded grey-brown and yellow-brown limestone breccia, calcarenite, sandy and silty limestone, marl and sandstone. The thickness was given as 200 m; the type section is 177 m thick (Guppy *et al.*, 1958, Table 3 and p. 98). The Beds overlie the Upper Devonian units of the Napier and Oscar Ranges, Fossil Downs area, and Bugle Gap, and are probably overlain by the Carboniferous Laurel Beds and unconformably overlapped by Permian sandstone of the Grant Formation (Guppy *et al.*, *op. cit*). They noted that the unit was within Teichert's *Productella* Zone which Teichert (1949) correlated with the doIV zone of Western Europe (late Famennian).

In the Explanatory Notes accompanying the 4-mile geological series maps of the area the distribution, lithology and thickness of the Fairfield Beds are tabulated (Veevers, 1958; Thomas, 1958). On the Noonkanbah Sheet the thickness is 60 m, and on the Lennard River Sheet 92 m. Veevers (1958) considers that the unit equates with the *Productella* limestone of Teichert; Thomas (1958) agrees that the faunas are the same. In both sets of notes the stratigraphic relationships are displayed on a figure adapted from Veevers (1959b, fig. 3). In both, the Fairfield Beds are shown interfingering with rocks of the reef complex including the Napier, Oscar and Virgin Hills Formations.

Taking into account the distribution, correlation and stratigraphic relationships of the Fairfield Beds mentioned by Veevers, and Thomas, it is apparent that the BMR Survey of 1947-58 considered the Fairfield Beds to be synonymous with Teichert's *Productella* limestone, identified by the presence of *Productella*, except for the massive limestones (Oscar and Napier Formations). Thus, virtually flat-lying and thinly bedded limestones now assigned to the Piker Hills Formation and perhaps the Bugle Gap limestone, and late Famennian birdseye limestone (mapped as Pillara Formation by Playford & Lowry, 1961), were included within the Fairfield Beds.

The term Fairfield Formation first appeared in the literature in 1958. Condon (p. 142), apparently quoting Thomas, refers to an area previously mapped as Upper Devonian Fairfield Formation which was found to be a different formation of Lower Carboniferous age. Jones (1959) uses Fairfield Formation in a text-figure and Beds in the text, as do Veevers & Wells (1961, Table 3). The term Fairfield Formation was synonymous with Fairfield Beds *sensu* Veevers & Wells (i.e. lacking the reef complex part of the *Productella* limestone). Veevers & Wells (1961) recognize the interfingering nature of the lower boundary of the Fairfield Beds and the coevality of the upper parts of the Fossil Downs, Napier, Geikie, and Oscar Formations, and the Bugle Gap Limestone, with the basal Fairfield Beds. They concluded that the characteristic lithology of the Fairfield Beds accordingly results from its deposition on the seaward edge of the shelf. The inshore equivalent of the Fairfield Beds is the uppermost part of the Virgin Hills Formation.

Playford & Lowry (1966) formally introduced the term Fairfield Formation. In doing so they altered the concept of the name. The basal part of the Fairfield Beds *sensu* Veevers & Wells (1961) was removed to the Piker Hills Formation (Playford & Lowry, 1966, p. 82) and to the Pillara Limestone (ibid., p. 62), and a considerable section, equivalent to all of the Laurel Formation of Thomas, 1959, was added.

The name was taken from the Fairfield Valley, in which scattered outcrops of the unit are known (Fig. 1).

The unit was defined as an interbedded sequence of limestone, shale, siltstone, and sandstone. The thickest section was given as 491 m in BMR Noonkanbah No. 2 (previously Laurel Downs No. 2), of which all but 128 m is Carboniferous. Playford & Lowry (1966, p. 94) were not convinced that the lower boundary of the Formation should be drawn at 567 m, and considered that the boundary could possibly be at 433 m, which would have excluded all rocks of Devonian age in this section.

The lower boundary was considered to be conformable on various beds of the reef complex — including back-reef (Pillara Limestone) in outcrop; and various fore-reefs units in wells, including Meda Nos. 1 & 2 and Hawkstone Peak No. 1. The unit is unconformably overlain by the Permian Grant Formation and in several wells it is overlain by the Carboniferous Anderson Formation (Playford & Lowry, 1966, p. 93).

The conodont study of Glenister & Klapper technically predates Playford & Lowry's bulletin, being published in July, 1966, whereas the bulletin bears no month of publication. Thus Glenister & Klapper's was the first detailed discussion of the Fairfield Formation. In their text-figure 2 the Fairfield Formation is recorded in the Bugle Gap area (probably the Red Bluffs outcrop); it is considered to have an age range of doIV-doVI.

The combined results of Playford & Lowry and Glenister & Klapper, led to the confusing position of having two units, one Devonian the other Carboniferous, placed in synonymy. Moreover faunas from the Carboniferous part were dated as Devonian, and the thickest section known was thought to be possibly all Carboniferous.

This concept of the Fairfield Formation found little favour with some subsequent workers. Roberts (1971), and Roberts & Jones (*in* Roberts *et al.*, 1972) both felt that the name Fairfield should be restricted to late Famennian rocks; Roberts *et al.* recognized the Piker Hills Formation as a valid unit; it had previously been mapped and considered as Fairfield Beds (see above). In addition they recognized that horizon K289 in the type section of the Fairfield Beds was probably late Famennian Pillara Limestone. Thus the Fairfield Beds *sensu* Roberts *et al.* is more restricted in its concept than Fairfield Beds *sensu* Guppy *et al.*, the lower boundary having been modified.

The concept of the Fairfield Beds has changed considerably since the original diagnosis of Guppy *et al.* (1958), in which it was equated with the *Productella* limestone (Veevers, 1958). Firstly Veevers & Wells (1961) recognized that some of the *Productella* limestone containing *Spinulicosta "Avonia" proteus* (Veevers) should be more correctly referred to the reef complex carbonates, including the Napier, Oscar, Geikie, and Fossil Downs Formations (now amalgamated into the Napier Formation *sensu* Playford & Lowry, 1966) and the Bugle Gap Limestone. Subsequently Roberts *et al.* (1972) agreed that some exposures previously mapped as Fairfield Beds belong to the Piker Hills Formation of Playford & Lowry, and at least part of the type section of the Fairfield Beds belongs to the late Famennian "Pillara Limestone".

The upper boundary has always been problematical. In the only detailed sequence which crosses the boundary Henderson *et al.*, (1963) placed the boundary at 433 m in BMR Noonkanbah No. 2, and included 109 m of sandstone, calcarenite, dolomite and siltstone which is younger than the youngest known outcrop of Fairfield Beds at Oscar Hills.

The name Fairfield has had a chequered history; it has been applied to four bodies of rock which have different limits. Firstly it included all rocks containing the *Productella*, (*Spinulicosta 'Avonia' proteus*) fauna apart from the Bugle Gap Limestone (Guppy *et al.*, 1958). Secondly it was restricted to *proteus* zone rocks younger than the massive fore-reef limestones in the Napier and Oscar Ranges (Veevers & Wells, 1961). Subsequently, the concept was changed by Playford & Lowry (1966) to include all the early Carboniferous platform carbonates (Laurel Formation) and to exclude thinly bedded late Devonian rocks associated with the reef complex. Finally the concept was restricted to Devonian post-reef platform carbonates by Roberts *et. al.* (1972). The type section DF 2 of Guppy *et al.*, 1958) was selected in an area far removed from the general outcrop area; subsequently much of this section has been included in the Pillara Limestone (Playford & Lowry, 1966; Glenister & Klapper, 1966, p. 838; Roberts *et al.*, 1972, p. 472).

Because of the considerable differences of opinion regarding the concept of the Fairfield Formation (and Beds) it is probably best to suppress Fairfield as a formation name.

THE TERM 'LAUREL'

The term Laurel Beds was introduced by Thomas (1957), who subsequently (1959) defined the unit as the Laurel Formation using the same criteria as was used to define the Laurel Beds.

The term Laurel Formation was first used by Condon (1958). He quoted from Thomas, although the quoted paragraphs do not appear in any of Thomas's reports (1956, unpubl.; 1957). No type section was designated, but an area of outcrop south of Oscar Range and northwest of Fitzroy Crossing was mentioned.

Condon reported that the formation consists of grey calcarenite and grey siltstone with a thickness of 183 m (this figure appears to be in error: all of Thomas's reports during the period 1956-59 refer to a thickness of 427-457 m). The faunal list equates with the faunal list of Thomas (1957) and the age was indicated as Tournaisian after Thomas (op. cit.).

Thomas (1959) defined the Laurel Formation as the sequence of fossiliferous calcarenite and siltstone of Lower Carboniferous age between the Upper Devonian Fairfield Beds and the Permian Grant Formation, probably in unconformable relationship to both (p. 21). The total thickness is of the order of 455 m according to Thomas (1959, p. 25), although there are problems in fitting together Type Sections I and II. Furthermore, anomalous dips are present on the black soil plains and the thickness may be exaggerated (see below).

The stratigraphic relationships of the Laurel Formation were considered to be unconformable by Thomas (1959, p. 30), who thought that the Laurel Formation was possibly deposited on an eroded surface of Devonian rocks. He drew attention to the considerable age difference then thought to exist between the Fairfield Beds (Late Devonian doIV or doV) and the Laurel Formation (late Tournaisian). Thomas reported an extensive fauna including brachiopods, pelecypods, nautiloids, gastropods, conchostracans, ostracods, sharks teeth, and a few corals and crinoids. The fauna shows marked affinities to Early Carboniferous faunas of Western Europe (Thomas, 1957); spiriferids of the *S. tornacensis* group indicate the Tournaisian (early Early Carboniferous).

In 1956 BMR Noonkanbah No. 2 (=Laurel Downs No. 2) penetrated at least 357 m of Laurel Formation and possibly as much as 379 m (Thomas, 1959, p. 31). The section included 174 m of shale with minor limestone, which apparently are not exposed, and thus were not included in Thomas's composite type section. Thomas (1959, p. 31) mentions the bore and does not exclude these beds from the Laurel Formation; neither does he explicitly include them. However he does state that higher parts of the Laurel Formation or other Carboniferous rocks may be present below the sand cover in the areas west of Laurel Downs homestead, implying the inclusion of these shales within the Laurel Formation.

BMR Noonkanbah No. 2 was drilled 3 km to the basinward side of the exposed Laurel Formation; it penetrated about 205 m of limestone, which probably represents the true thickness in the area rather than the 455 m measured in poor and scattered outcrop.

In their report on BMR Noonkanbah No. 2, Henderson *et al.* (1963) concluded that the upper 22 m of section which yielded Carboniferous fossils (54 — 76 m) was Permian, the fossils having been reworked. The base of the Laurel was placed at a change in lithology at 433 m. Open vugs from this horizon down to 520 m were taken as evidence of water circulation during a period of subaerial erosion before the deposition of the Laurel Formation. They concluded that the unconformity had been confirmed.

Conodont studies revealed an extensive microfauna. Glenister (1960, *fide* McWhae *et al.*, 1958) reported the presence of *Cavusgnathus*, a Middle Mississippian to Pennsylvania genus, from near Twelve Mile Bore, and also in Sisters No. 1 Well, from a depth of 5600' — 5603'6" (1707-8 m).

This discovery, together with the recovery of ostracods with Chesterian (late Mississippian) affinities led McWhae *et al.* (1958) to extend the Laurel Beds into the Namurian. Jones (1957, unpubl.; 1959) discusses only the affinities, and not the age, of the ostracod faunas; the Chesterian affinity was more by default than because of temporal relationships, inasmuch as known Early Carboniferous ostracod faunas were virtually restricted to the Chesterian.

Glenister (1960) reviews the conodont and ammonoid evidence for the age of the Laurel Beds. A single ammonoid species, *Imitoceras rotatorium* (de Koninck) suggested Tournaisian (early Early Carboniferous) whereas *Cavusgnathus* indicated middle to late Early Carboniferous. In order to reconcile this conflicting information Glenister concluded that the Laurel Beds were latest Tournaisian to Visean. It is now known that the cavusgnathoids recovered by Glenister belong to a homeomorphic genus, *Clydagnathus*, common in the earliest Carboniferous of the Bonaparte Gulf Basin (Druce, 1969).

Following its definition by Thomas, all workers accepted the Laurel Formation as a valid formal name (Jones, 1959, 1962; Veevers & Wells, 1961; Thomas, 1962) until 1966, when Playford & Lowry published a bulletin on the Devonian reef complexes. Although their paper was mainly concerned with the reef they did refer to the post-reef sediments, and included the Laurel Formation within their Fairfield Formation.

The name Fairfield was used because they were under the impression that it had priority. In fact the first appearance of both names in the literature was in the same paper (Thomas, 1957), and Laurel preceeds Fairfield. Accordingly the name Laurel has priority, even though the term Fairfield had been in colloquial use since 1942.

The view that the post-reef sequence belongs to a single rock unit has been supported by G. Playford (1971), who referred the Laurel Beds of Thomas to the upper Fairfield Formation of Playford & Lowry (1966). The 2nd edition of the Lennard River 1:250 000 geological map shows Fairfield Formation for outcrops previously mapped as Laurel Beds on the earlier edition.

However other workers favoured the retention of Laurel Formation; Roberts (1971) pointed out that no continuous section is known between the Fairfield Beds and the Laurel Formation. Furthermore a time gap was apparent in the faunas, a point amplified by Roberts & Jones (*in* Roberts *et al.*, 1972).They also note that although surface collections indicated a faunal break, sedimentation may have been continuous in the subsurface. This view was based on the recovery of a spore, *Hymenozonotriletes lepidophytus* Kedo, 1957 from Stumpys Soak No. 2 water bore (Balme & Hassell, 1962), which is indicative of the Devonian-Carboniferous boundary. This locality is on the basin margin side of the outcrop area, suggesting that the time-break may be due to non-exposure rather than a hiatus.

The term Laurel was the first published name to be applied to any of the sediments associated with the immediate post-reef period of sedimentation. Its later definition followed all the rules of stratigraphic nomenclature, and since it was formalised it has been used in a consistent manner by all workers.

PALAEONTOLOGY

BRACHIOPODS

Brachiopods, together with ammonoids, were used by Teichert to subdivide the Devonian of the Lennard Shelf into biostratigraphic units, the youngest of which, the *Productella* zone, was also recognised by Veevers — who equated it with the *proteus* brachiopod zone (1959b, p. 12).

This zone is present in both the youngest part of the reef-complex and in the sequence overlying the reef at one of Teichert's localities (No. 2), and was used to delineate the '*Productella*' limestone. Teichert (1949, p. 27) noted that although the fauna from locality N2 was similar in aspect to other faunas from the *Productella* limestone, it did differ in some respects; he considered these to be geographic variations. We now know that they are stratigraphic and that the other *Productella* limestone localities are older and can be referred to the Napier and Piker Hills Formations of Playford & Lowry (1966).

The brachiopods are described in Veevers (1959b), and Thomas (1959; 1971). Veevers' work comprises a systematic description of the Devonian species and included a zonation, based mainly on brachiopods, but also including some of Teichert's ammonoid zones. The youngest zone of *Avonia proteus* is equivalent to Teichert's *Productella* zone, the name given being the same species (Veevers, 1959b, p. 21).

The brachiopods of the Laurel Formation were listed by Thomas (1959) in a paper defining the Laurel Formation; also listed were species of gastropods, corals, ostracods (after Jones), conodonts (after Glenister), an ammonoid, and shark teeth. In a later paper (Thomas, 1971) the brachiopods were described systematically.

OSTRACODS

Ostracods were first discovered in samples both from BMR Noonkanbah No. 2 and surface outcrops. The fauna was divided into four assemblages, two Carboniferous (1, 2), and two Devonian (3, 4) (Jones, 1959); these were later amalgamated into assemblage A(3 and 4) and Assemblage C(1, 2) (Jones, *in* Veevers & Wells, 1961).

Assemblage A is characteristic of the Fairfield Beds whereas Assemblage C is confined to the Laurel interval 61-352 m (200' — 1155') in BMR Noonkanbah No. 2. In his later report Jones (*in* Veevers & Wells, 1961) announced the discovery of an intermediate Assemblage B in the interval 369 — 426 m (1210' — 1515')

CONODONTS

In 1966 Glenister & Klapper described the conodonts from the Upper Devonian reef complex systematically, and briefly touched on faunas recovered from the Fairfield Formation (*sensu* Playford & Lowry, 1966). Their specimens came from both the Fairfield Beds (WAPET Section A; GSWA 1053; G1/B30), its equivalent (Meda No. 1 Well, Core 11) and the Laurel Formation (DF 10-3, DF 10-5; GSWA 3240). They presumed that the meagre Laurel Formation faunas were late Devonian because of the presence of *Palmatolepis glabra* in sample GSWA 3240. The associated forms were referred to *?Scaphignathus veliferus*; previously Glenister (1960) had thought the specimens might be Carboniferous cavusgnathids. They are, in fact, clydagnathids of earliest Carboniferous age (Beinert *et al.*, 1971), and were recognized by Druce (*in* Roberts & Veevers, 1967) who considered the conodonts from the upper part of the Laurel Formation to be lower to middle Tournaisian. Subsequent collecting has failed to discover any further Devonian species in the area around GSWA 3240, and the initial recovery of *Palmatolepis glabra subsp. indet.* and *Prioniodina*? *smithi* remains an enigma.

One sample K289, is referred to the Pillara Limestone, immediately beneath the Fairfield Formation (Glenister & Klapper 1966, p. 838); however it is from the type section (DF2) of the Fairfield Beds (Guppy *et al.*, 1958, p. 98) and is from the base of the Fairfield Beds (Veevers, 1969, p. 159).

DETAILED STRATIGRAPHY

The latest Devonian and earliest Carboniferous platform carbonates and interbedded clastic rocks can be divided into three easily recognizable and mappable units, the Gumhole and Laurel Formations and the intervening Yellow Drum Sandstone. These formations are genetically related, and we have placed them in the Fairfield Group.

In one core hole, BMR Lennard River No. 1, a unit underlying the Fairfield Group was intersected; it is probably equivalent to the Luluigui Formation.

FAIRFIELD GROUP

The name Fairfield has been applied to Beds and to a Formation (see p. 4); the present usage is the same as the original stratigraphic use of the name in an unpublished report by Kraus (1942), and the Fairfield Group closely approximates to the interval referred to the Fairfield Formation by Playford & Lowry (1966).

The Fairfield Group consists of the Gumhole Formation, the Yellow Drum Sandstone, and the Laurel Formation. These three units form a lithogenetic sequence of limestone, siltstone, shale, and sandstone, with a few dolomite beds.

Transgressive phases are represented by the Gumhole Formation and the lower part of the Laurel Formation, and a regressive phase is represented by the upper part of the Gumhole Formation and the Yellow Drum Sandstone. All three units extend over much the same area and were deposited in the same environmental conditions, but can easily by recognized by differing colour and clasts.

The Group probably rests comformably on various rock units of the Famennian reef-complex on the Lennard Shelf and associated units in the Fitzroy Trough. The upper

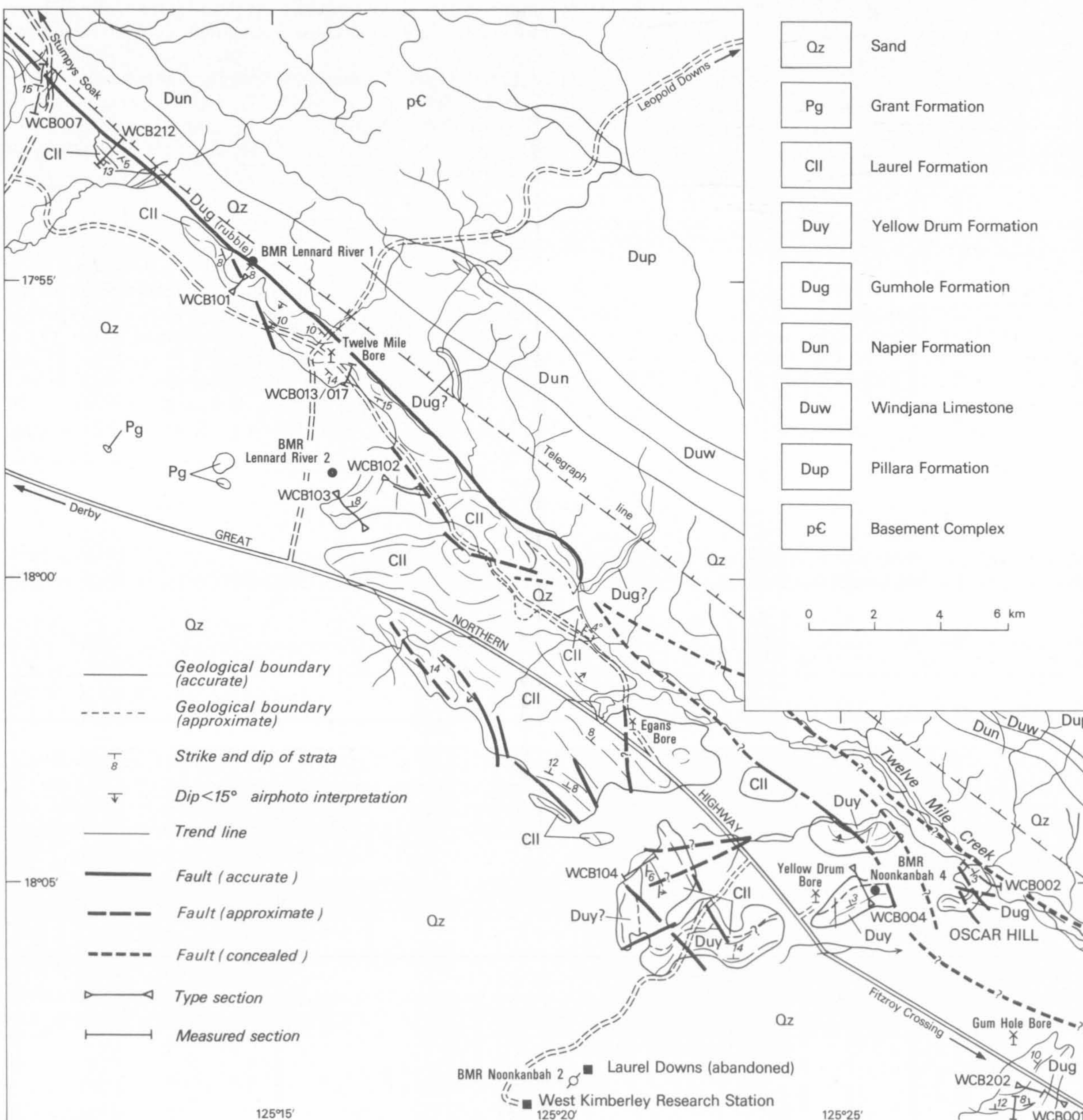

Figure 4. Geology of the Fairfield Group, Oscar Hill and Twelve Mile Bore.

boundary of the group is usually an unconformity with Permian sediments overlying the upper shale member of the Laurel Formation; rarely this member is conformably succeeded by sandstone of the Anderson Formation. The latter is considered to represent a late Early Carboniferous regressive phase of deposition with the development of thick, mostly non-marine, sediments in the Fitzroy Trough but with the emergence of, and consequent erosion from, the Lennard Shelf.

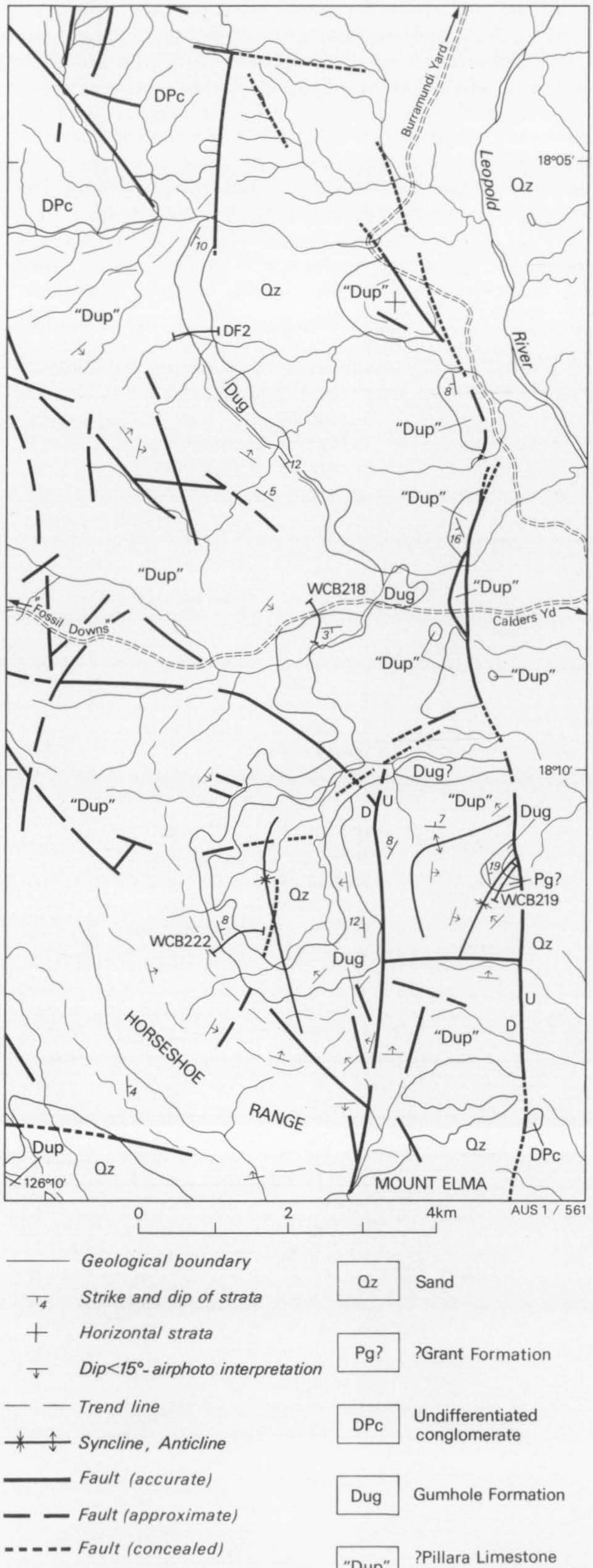

Figure 5. Geology of the Fairfield Group, Horseshoe Range.

GUMHOLE FORMATION (new name)

DEFINITION

The Gumhole Formation is named after Gumhole Bore (125°28'E,18°07'S) 18 km west-northwest of Fitzroy Crossing, Western Australia. The type section (WCB 001 and WCB 202) is on the Great Northern Highway 19 km west-northwest of Fitzroy Crossing, and 1.5 km southeast of Gumhole Bore (Fig. 4). The unit consists of about 70 m of limestone, siltstone, shale, and sandstone, with minor dolomite. The unit overlies an unnamed late Famennian birdseye limestone in the Horsehoe Range (Fig. 5) and at Red Bluffs (Fig. 6). In the area southwest of the Oscar and Napier Ranges it probably overlies the Luluigui Formation equivalent. It is conformably overlain by the Yellow Drum Sandstone, and is of latest Famennian (Upper Devonian) age.

The Gumhole Formation is broadly synonymous with the Fairfield Beds of Thomas (1957), and is equivalent to the Fairfield Beds of Roberts *et al.*, 1972, and Jones *et al.*, 1974; it forms the lowest part of the Fairfield Formation of Playford & Lowry, 1966.

AREAL EXTENT AND THICKNESS

The Gumhole Formation crops out in a linear zone for a distance of 280 km, from Red Bluffs in the southeast to the northwestern extremity of the Napier Range. It is recognisable in the subsurface in the Lennard Shelf region. In the Fitzroy Trough knowledge of the unit is restricted to one well, Yulleroo No. 1, and on the southern margin to two wells, Babrongan No. 1 and Frome Rocks No. 2. A limestone, (of dark colour in Frome Rocks No. 2), present

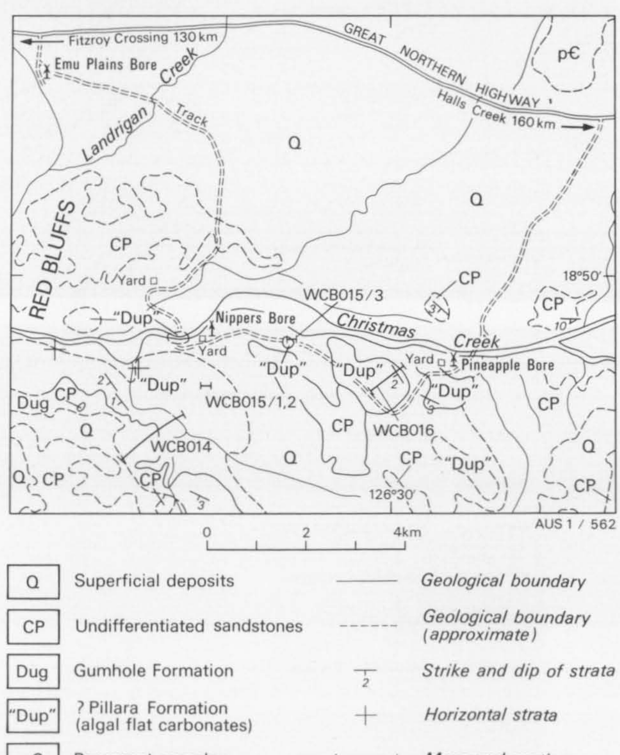

Figure 6. Geology of the Fairfield Group, Red Bluffs.

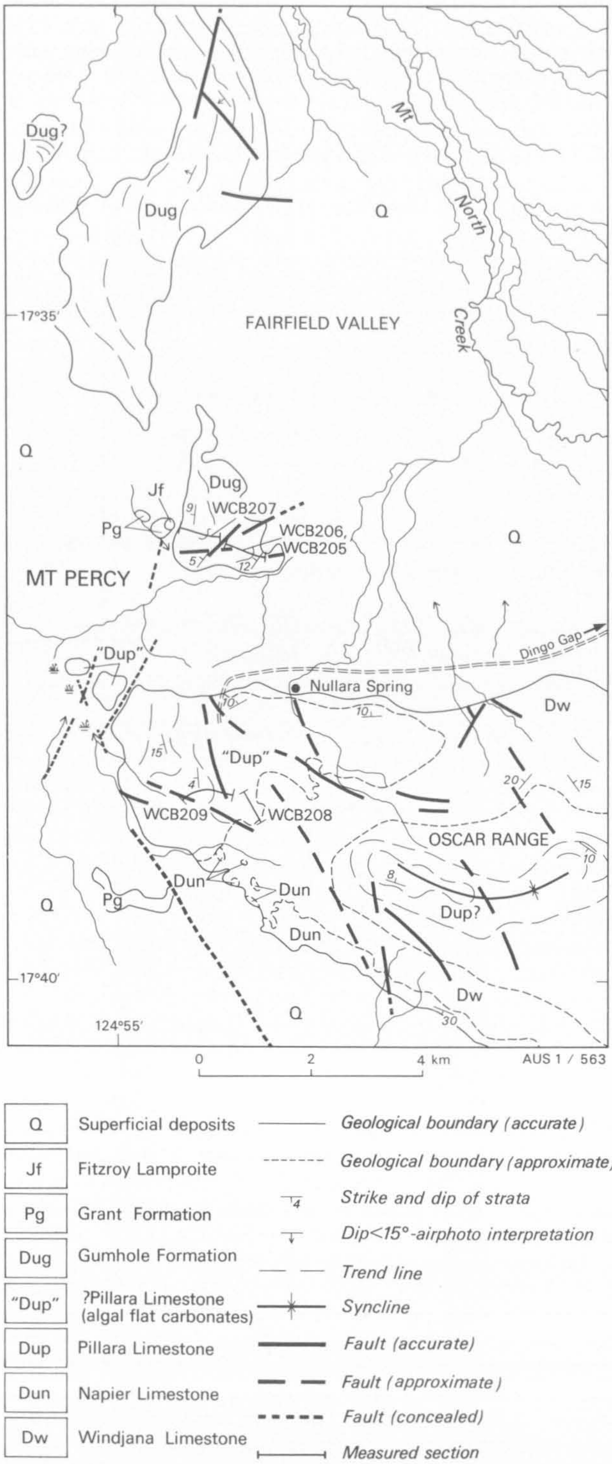

Figure 7. Geology of the Fairfield Group, Mount Percy.

in all three wells and of approximately the same age, is possibly contiguous with the Gumhole Formation.

The maximum thickness of continuous surface exposure is 71 m at the type section. To the northwest, at Mount Percy, faulting confuses the picture but the thickness could be as great as 150 m. At Oscar Hill, close to the type section, the thickness is 19.5 m; in the Horseshoe Range only 16 m is preserved; and at Red Bluffs, at the southeastern extremity of the outcrop, the thickness is 21 m.

However in the subsurface the thickness reaches a maximum of 369 m in Meda No. 1 well in the interval 1649-2018 m. Thicknesses in excess of 200 m are present in Sisters No. 1 well and also in Frome Rocks No. 2 in the 'Gumhole Formation equivalent'. Isopachs are presented in Figure 21.

Lithology

The unit consists of limestone, siltstone and shale, and sandstone, with minor dolomite. The limestone is commonly mottled light brown, pink to red and light green-grey; in places it is colour-laminated. The limestones vary between bioclastic, intraclastic and oolitic sandy grainstones (Figs 8,9). In some areas, such as Oscar Hill, the limestones are thick-bedded and cross-stratified (Figs. 8a, b).

The limestones are interbedded with grey-green siltstone, light to dark grey or grey-green shale, and grey-green claystone. These beds rarely crop out and are known mainly from the subsurface. The formation also contains some sandstone, generally near the base. It is orange-brown or pink, thin-bedded, calcareous, quartz-rich, poorly sorted, and friable.

The limestone-shale-sandstone ratio varies, but usually limestone is about 50 percent of the total thickness. At Oscar Hill (Fig. 8a) 98 percent of the section is limestone, but to the southeast in the Horseshoe Range and Red Bluffs area, limestone comprises only 44-46 percent of the sections.

No sandstone is recorded from sections at Oscar Hill or in the Horseshoe Range, but it forms 11 percent of the type-section, and at Red Bluffs, 39 percent of the section is sandstone.

Petrology

From the five sections that were studied in detail (WCB001, WCB002, WCB014, WCB202, WCB222), three lithofacies are recognized, namely:

A. Stratified and cross-bedded sandstones.
B. Siltstones
C. Limestones

Facies C can be subdivided into five subfacies, i) sandy bioclastic ooid grainstones, ii) bioclastic packstones, grainstones, and wackestones, iii) sandy bioclastic grainstones and wackestones, iv) bioclastic boundstones, packstones, wackestone, v) peloidal grainstones. Lithologic logs of these sections, outlining the facies, are tabulated in Appendix II.

Petrographic and diagenetic features of the facies and subfacies are described. The environmental interpretation of each facies is presented and integrated into the depositional history of the formation.

Facies A: Stratified and cross-bedded sandstones

This facies comprises fine to very fine-grained calcareous feldspathic sandstones. These are either poorly exposed as thin flaggy beds, which sometimes have small-scale cross-stratification; or better exposed in thicker units which are frequently planar laminated or cross-stratified. The well-sorted constituent grains comprise subangular quartz, plagioclase and potash feldspar, with muscovite and biotite. Optically continuous calcite cements (Fig. 8e) enclose the grains, some of which show signs of silica resorption. Grey-green disc-shaped claystone clasts are common at the base of the unit, and weather out to leave rusty, iron-stained casts.

A few ooids and brachiopod, bryozoan, ostracod, pelecypod and crinoid fragments are preserved, although most skeletal grains have been obliterated by pressure solution. Compaction zones within the beds exhibit very dense grain packing with straight and, less commonly, micro-sutured grain contacts. These zones impart the lamination to the sandstones, emphasize cross-laminae which were initially only recognized by orientated mica flakes, and probably represent an intermediate phase in the removal of calcite from the more friable and thus poorly exposed sandstone. Bedding surfaces tend to be undulose and irregular, modified by late-stage pressure solution.

Facies A is interpreted as shallow marine low-profile sand sheets. These probably accumulated in relatively gentle currents which continually sorted the sand during migration of the sheet. Few bottom dwellers were present and, significantly, skeletal material is poorly preserved. During migration of the sand sheet, lumps of the underlying clayey silt bottom were incorporated in the sands.

Facies B: Siltstones

Siltstones are very poorly exposed in the areas of low relief, and only slightly better exposed in incised gullies or creek banks. A distinction is made between fossiliferous and barren silts.

Subfacies B(i) Unfossiliferous siltstones

Subfacies B(i) comprises homogeneous, friable, poorly stratified rocks devoid of macrofossils. It has fair exposure only in Section WCB222, which follows an incised creek bank in the Horseshoe Range. The white to light buff siltstones are clayey and slightly calcareous. Induration varies with the amount of fine carbonate cement. A solitary large fragment of a *Leptophloeum* stem was found preserved in a basal calcareous silt.

The presence of *Leptophloeum* in this facies suggests a terrestrial siliciclastic source. Sedimentation was apparently continuous in low-energy conditions, with the virtual exclusion of any carbonate contribution. With little other data, the environment of deposition is interpreted as shallow marine.

Subfacies B(ii): Fossiliferous siltstones

This subfacies consists of widespread but poorly exposed homogeneous calcareous siltstones. They are yellowish olive-green when fresh, weathering to a light brown, and are distinctive where exposed, as at Oscar Hill (WCB 002) and Gumhole Bore (WCB 001). When weathered the more resistant skeletal and intraclast components remain to form fossil pavements on the surface.

The siltstones are friable and comprise mainly angular grains of quartz and feldspar, minor but noticeable biotite flakes, microcrystalline calcite, and a small component of green clay.

Skeletal and intraclastic components constitute about 16 percent of the rock. Tabulate corals form potato-shaped colonies encrusting disarticulated shells and large bryozoan fragments. Non-abraded brachiopods, bryozoans and solitary rugose corals are also present.

Bryozoans are dominant, with numerous encrusting forms on other bryozoans, lithoclasts, corals, brachiopods and algal thalli? (cylindrical moulds). Branch and fenestrate bryozoan fragments are less common. Brachiopods are abundant and include complete spiriferids, disarticulated productids, and their spines.

Solitary rugose corals, some with basal rootlets, may show several circular constrictions in the calyx, suggesting changes in rate of growth. Auloporid corals encrust these, as well as some lithoclasts which are partly indurated aggregates of skeletal fragments.

Deposition of the silts was in a low-energy shallow marine environment with close proximity to a land drainage system, which contributed the terrigenous silt fraction and transported most of the skeletal material. The autochthonous fauna is comprised only of the brachiopod *Rhipidomella*, encrusted by small gastropods and serpulids. The allochthonous fauna was transported during storms or floods from the two sources: a quiet-water hard ground colonized by crinoids; and a shallow-water, partly indurated substrate of sandy micaceous skeletal grainstones which produced intraclastic lumps that bore corals, bryozoans, spiriferids, rhynchonellids, and productids. Conical apertures within the encrusting bryozoans reflect their encrustation of possibly nonskeletal algal stems. The biota of this environment appears to have been extremely diverse and prolific prior to intermittent disruptions by fresh-water floods.

These fossiliferous siltstones are interpreted as intershoal silts.

Facies C: Limestones

Most exposures of the formation comprise limestone interbedded with recessive siltstone or sandstone. This facies is subdivided into five subfacies, which are more detailed than was attempted with the siliciclastics, as more can be interpreted from the diverse range of texture and skeletal constituents in the limestones.

Subfacies C(i): Sandy bioclastic ooid grainstones

Yellow to grey-red sandy bioclastic ooid grainstones, forming thin, and less frequently medium and thick beds, characterize the facies.

Ooids are the dominant constituent (Fig. 8d) with both normal mature and immature superficial forms developed. Abraded fragments of brachiopods, pelecypods, crinoids, bryozoans and fish, together with less abraded gastropods, solitary rugose corals, and disarticulated ostracod valves showing less but more variable abrasion, complement the ooids. In zones of more intense compaction and pressure solution, sand and sometimes crinoid and bryozoan fragments become more abundant. The thick beds have large-scale, superimposed, cut and fill structures with low-angle foresets. The subfacies contains terrigenous sand, and in some areas there is an increase upwards both of sand content and grain size; the latter increasing from fine to medium-grained sand.

The subfacies is extensive as a lower unit of the formation and is present at Gumhole Bore, Oscar Hill, Red Bluffs, and Mount Percy. Study of Recent ooids in the Bahamas (Newell *et al.*, 1960) shows that they accumulate in a discontinuous belt of shoals in very shallow water, with ridges being built up to mean sea level emerging at low tide.

By analogy, deposition of this subfacies is in a shallow marine environment, characterized by shoals and by moderately swift, probably tidal currents, sufficient to erode the large-scale cut and fill structures. Ooid and abraded skeletal fragments were in continual movement over these migrating shoals. The presence of sand and superficial ooids, as well as normal ooids, reflects an agitated environment with active carbonate precipitation. The incorporation of various types of skeletal fragments in these limestones occurred when the shoals migrated over suitable substrates.

Subfacies C(ii): Bioclastic wackestones, with packstones and grainstones

Subfacies C(ii) comprises thinly bedded, grey-green to buff or brown bioclastic packstones, grainstones, and wackestones which are silty and commonly interbedded with siltstones. Although these limestones have been pressure solved (stylolitic lamination) and slightly recrystallized, the dominant skeletal components are still discernible.

Brachiopods, crinoids and bryozoans are the dominant allochems, with minor amounts of well-abraded pelecypod and fish fragments; well-preserved corals, ostracods, and the charophyte alga *Umbella sensu* Maslov, 1966. The brachiopods are commonly complete and the crinoid ossicles may still be partly articulated, both forms having associated spines present. The bryozoans include branching, encrusting and fenestrate forms. The autochthonous fauna is abundant, diverse, and shows minimal disturbance including the preservation of delicate fenestrate bryozoans. The introduced skeletal elements, pelecypod and fish fragments, are significantly abraded.

In most of the rocks, variable amounts of micritic matrix implies a probable bioclastic wackestone before early diagenetic solution removed significant proportions of the carbonate mud. Original grainstones are discerned by having more abraded skeletal constituents. This subfacies occurs locally in the Gumhole Bore (WCB 001) and Oscar Hill (WCB 002) areas.

The bioclastic packstones, grainstones, and wackestones contain finely disseminated pyrite suggesting precipitation in a mildly reducing, low-energy, shallow water, open marine environment. Carbonate muds readily accumulated, but during periodic conditions of higher energy, winnowing of the sediment modified the wackestones to packstones and grainstones.

The subfacies is considered the result of open, shallow marine platform sedimentation.

Subfacies C(iii): Sandy bioclastic grainstones and wackestones

This subfacies is characterized by thin bedded yellow-brown to red-brown sandy bioclastic grainstones, and buff to light grey bioclastic wackestones; less abundant thicker beds commonly have cut-and-fill structures.

Bryozoans, and crinoid ossicles and spines, are the dominant skeletal types. The bryozoans are either branching or encrusting forms, with limonite and calcite infilling the zooecial pores. Large brachiopods are abundant, some being complete with external algal borings, while others are abraded. Productid spines are common. The remaining skeletal contribution is from recrystallized pelecypod fragments; large, low-spired gastropods, complete and disarticulated, abraded fish fragments, slightly abraded auloporids; and solitary rugose corals and *Umbella*. *Girvanella* encrustations and oncolites (Fig. 8f) are frequent in the upper part of the subfacies. The grainstones contain varying amounts of fine and, less commonly, medium to coarse-grained quartz sand. Ooids, both mature and superficial, as well as green clay clasts, occur in these sandier grainstones. Limestones of this subfacies show early solution and late pressure-solution features. Distribution of the subfacies is restricted to the Gumhole Bore (Section WCB202) and Horeshoe Range (Section WCB 222) areas.

Discontinuous moderate and high-energy conditions produced an alternation of sandy grainstones and minor silts, the former having cut-and-fill structures developed during higher energy conditions, which winnowed and transported the silt to lower energy environments, where productids were a notable part of the fauna. Overall, the dominance of bryozoan and crinoid ossicles, and brachiopods with intense algal boring, are indicative of impoverished fauna, due to limited nutrients in shallow water with normal salinities. The upper part of the subfacies has abundant ooids, *Girvanella* oncolites, and encrustations, caused by shoaling and an increase in energy conditions.

The subfacies is interpreted as shoal and restricted marine platform sediments.

Subfacies C(iv): Bioclastic boundstones, with packstones and wackestones

Subfacies C(iv) comprises thin to thick-bedded yellow bioclastic boundstone, packstone and wackestone, with interbedded siltstone. Thick beds of mottled boundstone, commonly forming mounds up to one metre in diameter, dominate the lower part of the facies; they are generally overlain by beds of wackestone and packstone.

The boundstone comprises colonies of fasciculate rugose corals and crinoids which provide the basic framework for encrustation by bryozoans or fenestrate and laminated non-skeletal algae and *Girvanella*, the overall structure being cavernous with large interconnecting pores. Numerous early diagenetic solution vugs are infilled with vadose silt, producing geopetal structures.

Complete brachiopods with algal-bored external surfaces, gastropods, ostracods, fish fragments and peloids are present in all limestones, showing minimal abrasion. *Girvanella* encrusts fenestrate bryozoans (Fig. 9a) and other skeletal components.

In an environment with low-energy conditions and moderately shallow water, small biohermal domes were distributed randomly over an open-marine platform and occupied less than 5 percent of the area which was otherwise blanketed in packstones, wackestones, and silts. The domes were generally low hemispheres with diameters of one to two metres, probably no more than one metre in height. This relief may have been sufficient for the upper bioherm surface to be within a more turbulent, wave-agitated zone providing an adequate nutrient supply as well as winnowing away fine sediment.

This subfacies has been recognized only in the type area (Section WCB001, 202), and is interpreted as an open-marine environment with scattered bioherms. The surrounding muddy sediments supported and accumulated from a normal marine fauna.

Subfacies C(v): Peloidal grainstones

This subfacies is composed of thin to medium-grained, regularly bedded peloidal grainstones with a characteristic mottled greenish and greyish-yellow colour.

It is only present in the southeast region, at Horseshoe Range (Section WCB222) and Red Bluffs (Section WCB 014) as thin intermittent beds; fenestrate mudstones are associated with the grainstones at Red Bluffs.

In the grainstones, the dominant components are peloids of varying sizes, rounded to angular in shape, and with an aphanitic texture. A few, however, have an internal fabric suggestive of a faecal origin (Scoffin, 1973). Also present in small amounts are quartz, silt, calcispheres, complete cement-filled ostracods, crinoid ossicles, and algal-coated gastropod and pelecypod fragments. The molluscan shells are usually recrystallized and identifiable only by their micritized shell margins. Early compaction of peloids has produced grumous textures in places, but this has been partially obscured by later recrystallization and intense stylolitic compaction.

The subfacies is interpreted as a sequence of intertidal algal flat sediments. The fenestrate carbonate muds present have comparable internal fabrics to recent intertidal algal sediments at Shark Bay (Davies, 1970). After dessication, the sediments were perhaps reworked to mud lumps, some of which retained recognizable fenestrae. Minor terrigenous and skeletal sands were also introduced to this environment. This skeletal and locally reworked fenestrate material was subsequently micritized by endolithic algae, abraded, and then deposited as peloids. A few gastropods probably grazed this substrate, but surprisingly there is no evidence of fish habitation. This may have been because of abnormally high salinities developed by restricted water circulation in the environment.

The subfacies has a diverse range of skeletal components in the limestones, confirming a marine environment. The presence of endolithic algal filaments in allochems (as

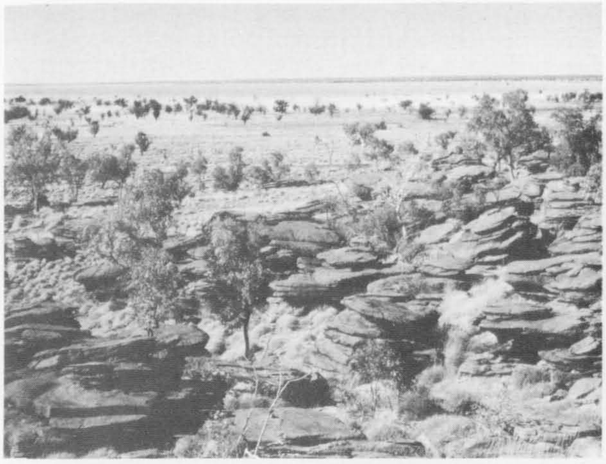

Figure 8a. Cross-stratified skeletal grainstones; Gumhole Formation, Oscar Hill (locn WCB 002).

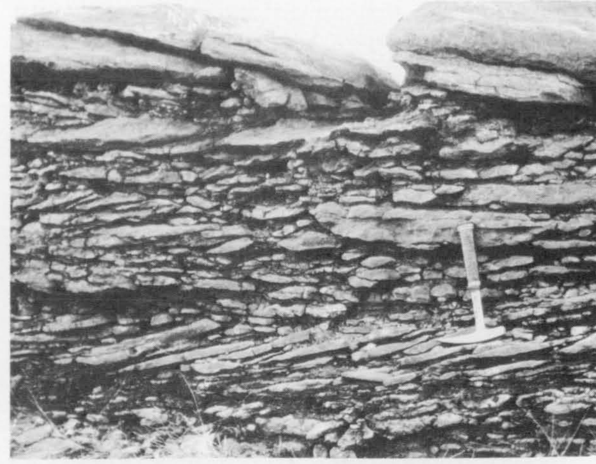

Figure 8b. Cross-stratified skeletal grainstones; Gumhole Formation, Oscar Hill.

Figure 8c. *Loptophloeum;* Gumhole Formation, Horseshoe Range (locn WCB 222/2).

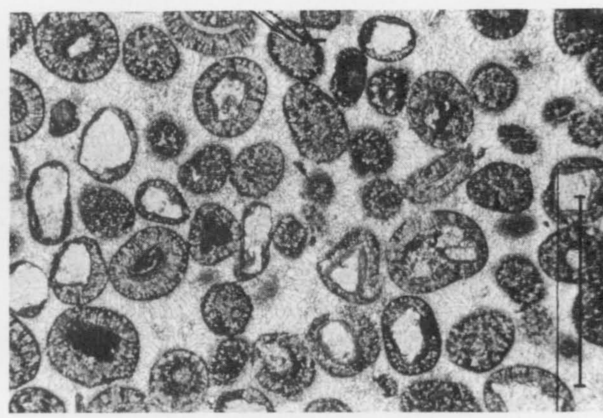

Figure 8d. Ooid grainstone; Gumhole Formation, type section (locn WCB 001/15).

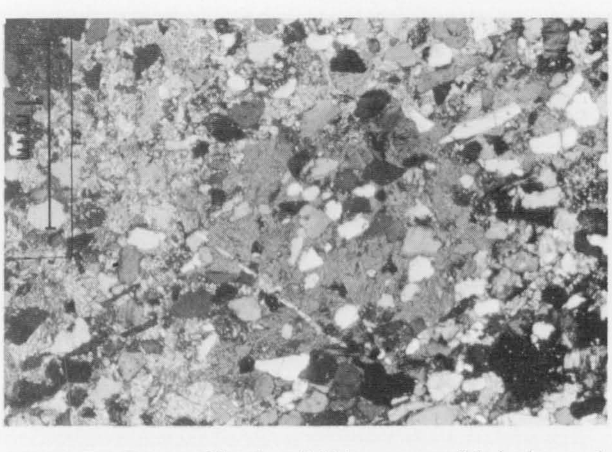

Figure 8e. Recrystallized poikilitic cement fabric in sandstone; Gumhole Formation, type section (locn WCB 001/2) x 37, crossed polars.

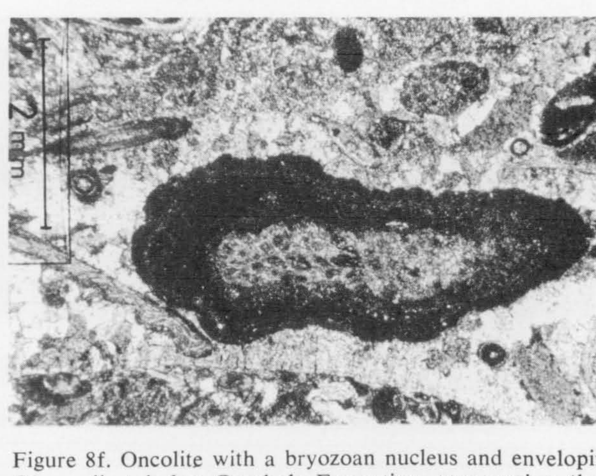

Figure 8f. Oncolite with a bryozoan nucleus and enveloping *Girvanella* tubules; Gumhole Formation, type section (locn WCB 202/27) x 18

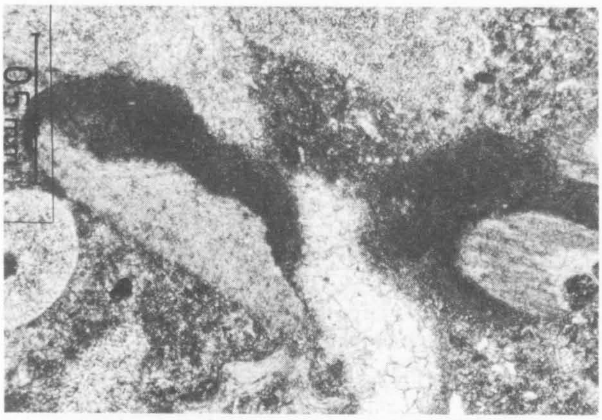

Figure 9a. *Girvanella* tubules encrusting parts of brachiopod and bryozoan fragments; Gumhole Formation, type section (locn WCB 202/14) x 58

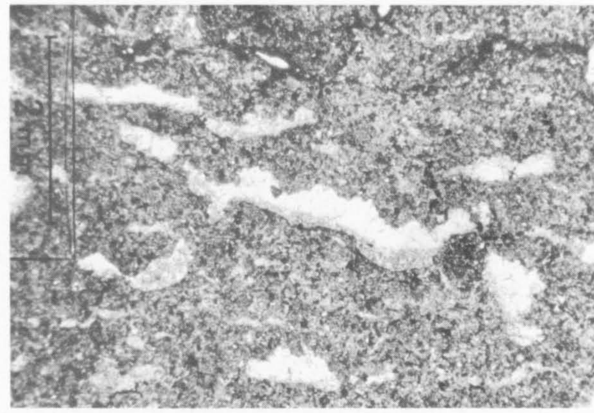

Figure 9b. Elongate solution vugs initiated from fenestrae —with irregular upper margins and crystal silt geopetals; Gumhole Formation, Red Bluffs (locn WCB 014/12) x 18

Figure 9c. Skeletal packstone with extensive removal of mud by solution—note infiltered sediment under the brachiopod valve; Gumhole Formation; Gumhole Bore (locn WCB 201/6) x 15

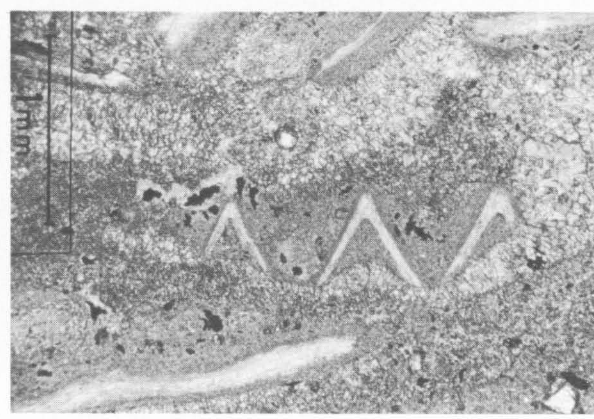

Figure 9d. Brachiopod valve truncated by a solution vug; Gumhole Formation, type section (locn WCB 001/8) x 37

Figure 9e. Solution cavity infilled by crystal silts; a period with no solution allowed a cement fringe to develop before further solution and deposition; Gumhole Formation, type section (locn WCB 001/8) x 37

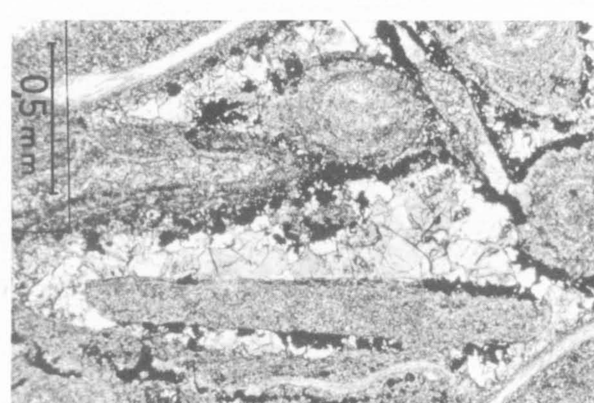

Figure 9f. Pyrite lining solution vugs between grains. Non-ferroan dogtooth and ferroan blocky calcite cements followed; Gumhole Formation (locn WCB 001/8) x 58

observed in recent carbonate sediments by Golubic, 1969), oncolites, and encrustations of *Girvanella*, indicate a water depth of less than 10 metres. With the common interbedding of terrigenous silt and some sand with the limestone, it seems that there was a continuous terrigenous supply and sedimentation in areas adjacent to the carbonate environments. The dispersed occurrence of these terrigenous bodies probably reflects the multidirectional progradation of the sand sheets.

Limestone Diagenesis

The salient diagenetic features of the limestones of each area studied are tabulated for comparison in Table 1. This sequence of events differs in some facies, and in such cases the variations were mentioned in the subfacies description.

In the muddier sediments, shortly after deposition and possibly prior to lithification, micrite was either partially or totally removed from some wackestones and packstones (Fig. 9c) — either by solution or interparticle erosion — producing grainstone textures. In the packstones, irregular vugs rarely crosscut allochems (Fig. 9d). These vugs were partially infilled by crystal silt.

Pyrite was precipitated in very fine aggregates mainly on, or in, bioclasts (Fig. 9e), especially the internal pores of crinoid ossicles. At this stage, syntaxial calcite-cement rims developed rapidly on crinoid fragments which were exposed to pore waters. This occurred contemporaneously with the precipitation of ferroan-poor acicular calcite fringes or drusy mosaic over the remaining pore surfaces. In some cases the sediment is zoned, produced by the variation of fringe thickness of these cements. During an increase of ferroan ion content in the pore fluids, cementation continued, with an increasing ferroan content of the calcite cement, and occurred both gradationally and abruptly (Fig. 16c) as revealed by straining techniques. In some cases there were discontinuities in cementation, most noticeably when both cement fabric and composition varied together. The pyrite and calcite cement fringes were repetitive in some skeletal shell infills.

Following this major lithification phase, indiscriminate solution of allochems and cements was common. Cementation within the resultant vugs followed the same pattern as the earlier cementation — pyrite, ferroan-poor calcite, and ferroan-rich calcite (Fig. 9f), but with different cement fabrics, namely dogtooth rims followed by blocky calcite infill.

Stratigraphic Relationships (Fig. 3)

Because of the relatively poor outcrop and lack of marker beds, stratigraphic relationships have necessarily been determined from sub-surface information and general age considerations of the associated strata. Some relationships are deduced intuitively from consideration of probable facies relationships. In the two sections at Horseshoe Range and Red Bluffs, the Gumhole Formation directly overlies a birdseye limestone of late Famennian age. This has previously been mapped as Pillara Formation by Playford & Lowry (1966), but, because of lack of continuity with Frasnian rocks of similar lithology, it may be considered a separate unit. In the subsurface the Gumhole Formation overlies Famennian birdseye limestone in area southwest of the Napier Range, at Blackstone No. 1; in the same area it overlies Precambrian schists in Langoora No. 1 and the Late Devonian Reef Complex in Meda No. 1. Elsewhere in the subsurface the Gumhole Formation overlies the Luluigui Formation, or its equivalent, as in Sisters No. 1 and Palm Springs No. 1, and other wells in the Napier Range area. In BMR Noonkanbah No. 2 the Gumhole Formation overlies a sequence of redbrown and green micaceous siltstones with minor beds of calcarenite, quartz sandstone and limestone breccia. This unit is probably equivalent to the Luluigui Formation, but the slightly different lithology suggests that it may be a basinward equivalent of the Napier Formation, which is interpreted by Playford & Lowry (1966, p. 65) as forereef, and, in places, an interreef deposit.

The Gumhole Formation is overlain by the Yellow Drum Sandstone in the Oscar Hill area although no contact can be seen. In the subsurface the Gumhole Formation is succeeded by sandstone and/or dolomite interbedded with siltstone, which is referred by us to the Yellow Drum Sandstone.

Palaeontology and Age

The Gumhole Formation is extremely fossiliferous and includes brachiopods, pelecypods, corals, bryozoans, nautiloids, fish, conodonts, ostracods, algae, and a microflora.

The brachiopods have been described by Veevers (1959b) who records *Schuchertella dromeda* Veevers, *"Avonia" proteus* Veevers, *Camarotoechia lucida* Veevers, *Athyris oscarensis* Veevers, and questionably *Schizophoria apiculata* Veevers. Veevers records *Meristella* (?) *caprina* Veevers from the Station Creek and Mount Percy areas, but it is not clear whether they are from exposures which we

TABLE 1. DIAGENESIS OF LIMESTONES, GUMHOLE FORMATION

Events	*Type Section (001, 202)*	*Oscar Hill (002)*	*Horseshoe Range (222)*	*Red Bluffs (014)*
Sedimentation	*	*	*	*
Solution, removal of muds producing vugs	*			
Infil of vugs by crystal silt	*			
Pyrite precipitation	*			
Syntaxial cement growth on crinoids	*	*		
Acicular fringe cement of ferroan poor calcite	*	*	*	*
	discontinuity			
Acicular and drusy ferroan-rich calcite cement	*	Crystal silt	*	*
Compaction	*	*	*	*
Solution	*		*	*
Pyrite precipitation	*	*		
Ferroan-poor drusy calcite cement	*	*	blocky	blocky
Ferroan-rich blocky calcite cement	in solution vugs	*	*	*
Stylolitic solution	*	*	*	*

* presence

would refer to the Gumhole Formation or from the underlying Luluigui Formation equivalent.

Pelecypods are abundant but are mainly fragmentary. A large species of a pecten is present in the type section.

Solitary corals are abundant and may show 90° rotation in growth axis suggesting that the normally upright skeletons have been felled by periodic storms. The species include *Catactotoechus irregularis* Hill, *C. tenuis* Hill, *Zaphrentoides ? excavatus* Hill and *Temnophyllum* sp. (Hill & Jell, 1970).

Bryozoans from the Gumhole Formation include *Percypora tubulata* Ross from Mount Percy, *Fitzroyopora oscarensis* Ross, *Coelocaulis maculosa* Ross and *Discotrypa* sp. A; other species recorded from the Fairfield Beds by Ross (1961, p. 17) are from strata now referred to the Piker Hills Formation. In addition *Granivallum fisulosum* Ross, is from the late Famennian birdseye limestone in the Horseshoe Range. From the location information given by Ross it is difficult to decide whether or not *Percyopora occidentalis* Ross occurs in the birdseye limestone or in the Gumhole Formation, although the former is more likely.

Straight nautiloids are abundant in one or two silty layers in the Gumhole Formation. So far only one species has been described from the formation, *Cavutoceras inequiseptatus* (Teichert); other forms described by Teichert from the Lennard Shelf appear to be from formations other than the Gumhole.

Several sandy beds toward the top of the Gumhole Formation are relatively rich in fish remains. The fauna is still to be studied in detail, but it includes dipnoan (dipterid) toothplates, and arthrodiran plates including a brachythoracid arthodire (G.C. Young pers. comm.).

The conodonts have been described by Nicoll & Druce (in prep). They are typically shallow-water forms and pelekysgnathids, icriodids and simple cones, together with spathognathodids, make up the fauna. European zonal species are rare; a single specimen of *Spathognathodus ziegleri* Rhodes, Austin & Druce was recovered from limestone at Oscar Hill (WCB 002). Other species include *Pelekysgnathus australis* Nicoll & Druce (a multielement form), *Acodina* sp. A and sp. B, *Angulodus compressa* (Huddle), *A. pergracilis* (Ulrich & Bassler), *Hibbardella*? *helmsi* Nicoll & Druce, *H.* cf. *H. insignis* Huddle, *H.*cf. *H. micra* (Cooper), *H.* sp. nov. Druce 1969, *Hindeodella brevis* Branson & Mell, *H. corpulenta* Branson & Mell, *H. subtilis* Ulrich & Bassler, *Icriodus platys* Nicoll & Druce, *Ozarkodina abnormis* Branson & Mehl, *Polygnathus communis collinsoni* Druce, *Prioniodina*? *symentrica*, *Spathognathodus aciedentatus* (E.R. Branson), *S. crassidentatus* (Branson & Mehl), *S. mehlbrai* Nicoll & Druce, *Synprioniodina regularis* E.R. Branson, and gen. et. sp. indet. B.

Ostracods are also abundant in the subsurface Gumhole Formation. Jones (*in* Veevers & Wells, 1961) reports an extensive fauna from BMR Noonkanbah No. 2, especially in the interval 541-966 m; the limits of the Gumhole Formation are taken as 539-567 m in this well. Recently Jones (pers. comm.) has identified ostracods from this interval which also occur in the Buttons Beds of the Bonaparte Gulf Basin (Jones, 1969). They include *Cavellina* sp. A Jones, *Coeloenellina* sp. cf. *C. fabiformis* Kesling & Kilgore, *Indivisia variolate* Jones, and *Knoxiella* sp. A Jones. Jones has also determined the *Eridoconcha* sp. A, also known from the Bonaparte Gulf Basin.

Spore assemblages have been reported by Balme & Hassell (1962) from subsurface samples from the Lennard Shelf; the samples are from the "Luluigui Formation equivalent", the Gumhole Formation, and the Yellow Drum Sandstone. The flora appears to change little in this interval and it is difficult to determine the flora of the Gumhole Formation from the information supplied. However the following species do occur in the Gumhole Formation: *Leiotriletes pulverus* Balme & Hassell, *Punctatisporites iterabilis* Balme & Hassell, *Punctatisporites* sp. cf. P. *solidus* Hacquebard, *Planisporites furfuris** Balme & Hassell, *Granulatisporites frustulentus** Balme & Hassell, *Convolutispora fromensis** Balme & Hassell, *Camptotriletes* sp., *Reticulisporites ancoralis** Balme & Hassell, *Archaeotriletes porrectus* Balme & Hassell, *Pulvinispora depressa* Balme & Hassell, *Stenozonotriletes* sp. cf. *S. recognitus* Naumova, *Hymenozonotriletes scorpius* Balme & Hassell, *Leiozonotriletes naumovae* Balme & Hassell (=*Hymenozonotriletes lepidophytus* Kedo), *Diaphanora riciniata** Balme & Hassell. All these forms are also recorded from the Yellow Drum Sandstone, and those marked with an asterisk extend into the Laurel Formation. Balme & Hassell (p. 25) concluded that the microflora implies 'a strongly differentiated pteridophyte flora around the margins of the Canning Basin in late Devonian time. This flora is known to have contained a lycopod element. From the structural and ornamental complexity of some of the spore types, sphenopsids and ferns were almost certainly also represented'. The plant *Leptophloeum* occurs in section WCB222 in the Horseshoe Range (Fig. 13).

All the palaeontological evidence indicates a late Famennian age for the Gumhole Formation. The few zonal species which do occur, *Spathognathodus ziegleri* Rhodes, Austin & Druce, and *Hymenozonotriletes lepidophytus* Kedo, indicate the doV1 zone; however *H. lepidophytus* does extend into the Strunian (tn1a) which is latest Famennian.

GEOCHEMISTRY

Geochemical analyses were mainly confined to the limestone beds (Druce & Radke, 1977) which have a mean Ca content of 34.68 percent and are thus relatively pure. Magnesium concentrations (mean 0.17 percent) are very low and generally the beds are pure calcite, in some places having a $CaCO_3$ content of 99.5 percent.

The Gumhole Formation has relatively high concentrations of Mn and, in the soluble fraction, Fe; both are concentrated in the cements. The high levels are possibly due to arid climate and nearshore deposition (Druce & Radke, *op. cit*).

Minor element concentrations are average with reference to worldwide carbonate analysis, except for Pb which is relatively abundant with a mean concentration of 36 ppm and a range of 5-670 ppm.

Some geographic variations in major element concentrations were noted by Druce & Radke (*op. cit*). Insolubles and Fe increase southeastward, whereas Sr and Ca have the opposite trend; these trends are also seen in the overall limestone/clastic ratios which show an increased clastic content southeastward.

The only statistically significant geographic variation detectable in the minor element geochemistry is with respect to Cu, which has a highest concentration in the Red Bluffs area. Possible explanations are either a higher influx of Cu from Red Bluffs source area, or subsequent concentration during diagenesis. However the values (mean 10.7 ppm) are too low to provide sufficient information to explain the variation.

REGIONAL VARIATION OF ENVIRONMENTS

Sections of the Gumhole Formation were studied in four areas along the margin of the Fitzroy Trough (Fig. 1) to establish the regional and stratigraphic distribution of the described facies. In Figure 10 these facies are superimposed on the sections and comparisons are attempted — although

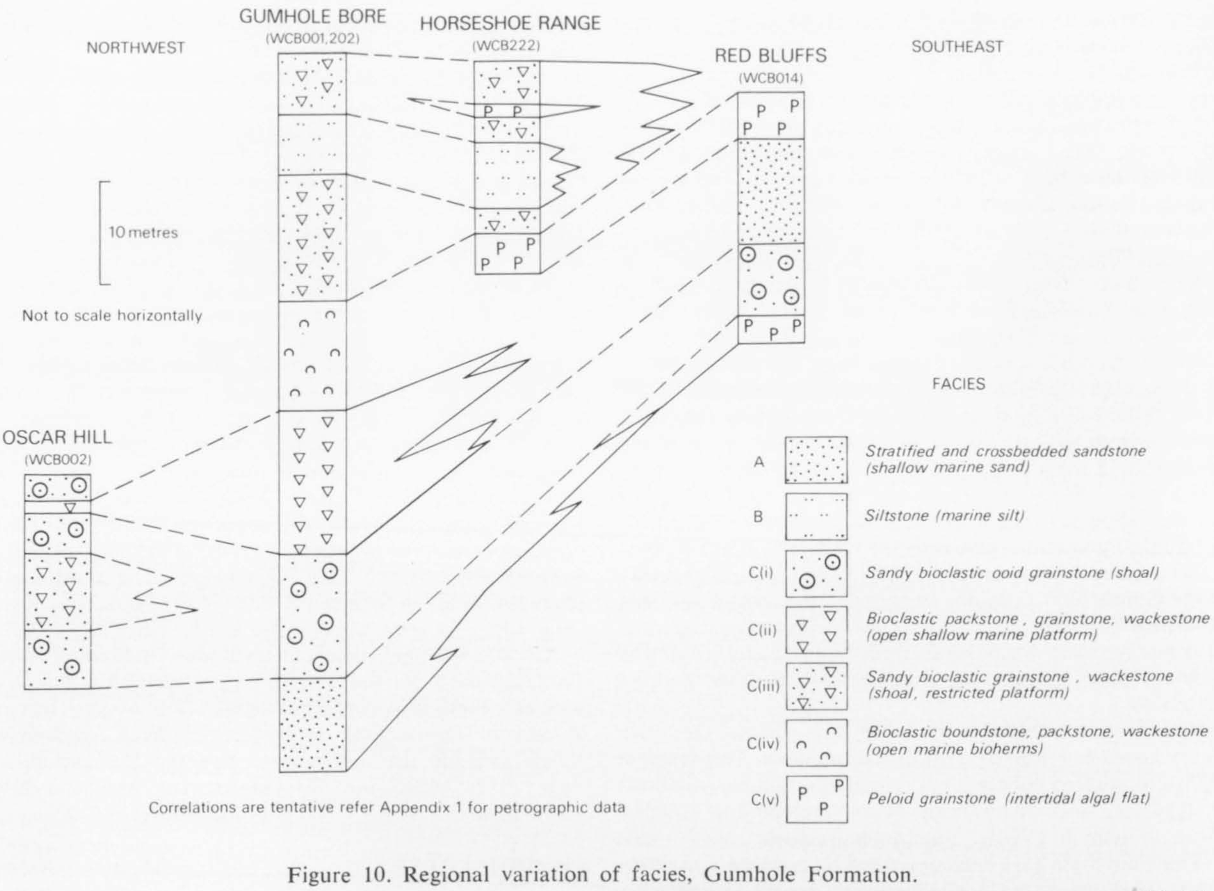

Figure 10. Regional variation of facies, Gumhole Formation.

these are of questionable credibility because no marker horizons are known. The sections are arranged from northwest to southeast over a distance of 150 km.

Oscar Hill (Section WCB 002) represents mainly shoal environments characterized by ooid and bioclastic sands, with a brief period of open marine conditions.

The thickest and most variable sequence is present at the type section near Gumhole Bore (WCB 001, 202). Shallow marine siliciclastic and carbonate sand shoals were present initially, and followed by open-marine sedimentation with scattered bioherm development. Lithofacies from regressive sedimentation followed; shoals, intershoal and restricted marine. Similar to this upper regressive phase of the type section is the Horseshoe Range sequence (WCB 222) — where the shoal and intershoal pattern developed over an intertidal algal flat environment — the latter considered transitional with the underlying Upper Famennian 'birdseye limestone', which was referred to as the Pillara Formation by Playford & Lowry (1966) and "Pillara" limestone by Roberts *et al,* (1972). This transitional, intertidal algal flat environment is also recognised at the base and top of the Red Bluffs sequence (WCB 014), but because of increased proportions of calcareous sandstone, has similarities also to the Yellow Drum Sandstone. Within the WCB 014 section a sandy ooid shoal environment is similar to that interpreted for the base of the type section.

Depositional History

It is feasible to assume that all the environments described earlier coexisted in a limited area, and on this assumption a model of sedimentation patterns was constructed so that all environmental changes observed in section were accommodated in the model illustrated in Figure 11. In addition, the resultant sequence is represented in block diagram format. The progressive sequence of environments in Figure 10 implies an early transgressive phase, which is also shown in Figure 1, followed by a stillstand period and final regression.

The region of sedimentation was a broad marine platform which sloped gently seawards, with only minor relief. Overall, the facies were deposited in shallow marine waters, probably less that 15 metres deep; wave-modified tidal currents are considered the main energy source, especially for the reworking in the shoals.

The platform is subdivided into three distinct zones, namely the open platform, shoal with intershoal areas and restricted platform, and the intertidal zone.

On the *open platform* shallow marine and bioherm environments coexisted. In the relatively deeper water, tidal currents were not as erosive and finer carbonates accumulated. The faunas were diverse and quite prolific as a result of normal salinities and the probable abundant supply of nutrients.

The *shoal, intershoal, restricted platform* zone has the most variable bathymetry, shallower than the open platform and with more variable energy conditions and sediment patterns. Ooid and bioclastic shoals migrated in one general direction over the silty intershoal areas, which had a fairly abundant fauna. Behind the shoals, in lower energy conditions, silts and muddy carbonates accumulated with a fairly limited fauna, probably as a result of slightly higher salinities.

Cutting across all zones were the subtidal drainage channels of rivers which distributed terrigenous sediments. With the fresh-water influxes, areas adjacent to these channels were indurated and provided the suitable substrate for colonization by a diverse fauna — until following incursions of floodwaters killed and transported it to the intershoal areas.

In the initial stages, the Gumhole Formation was trans-

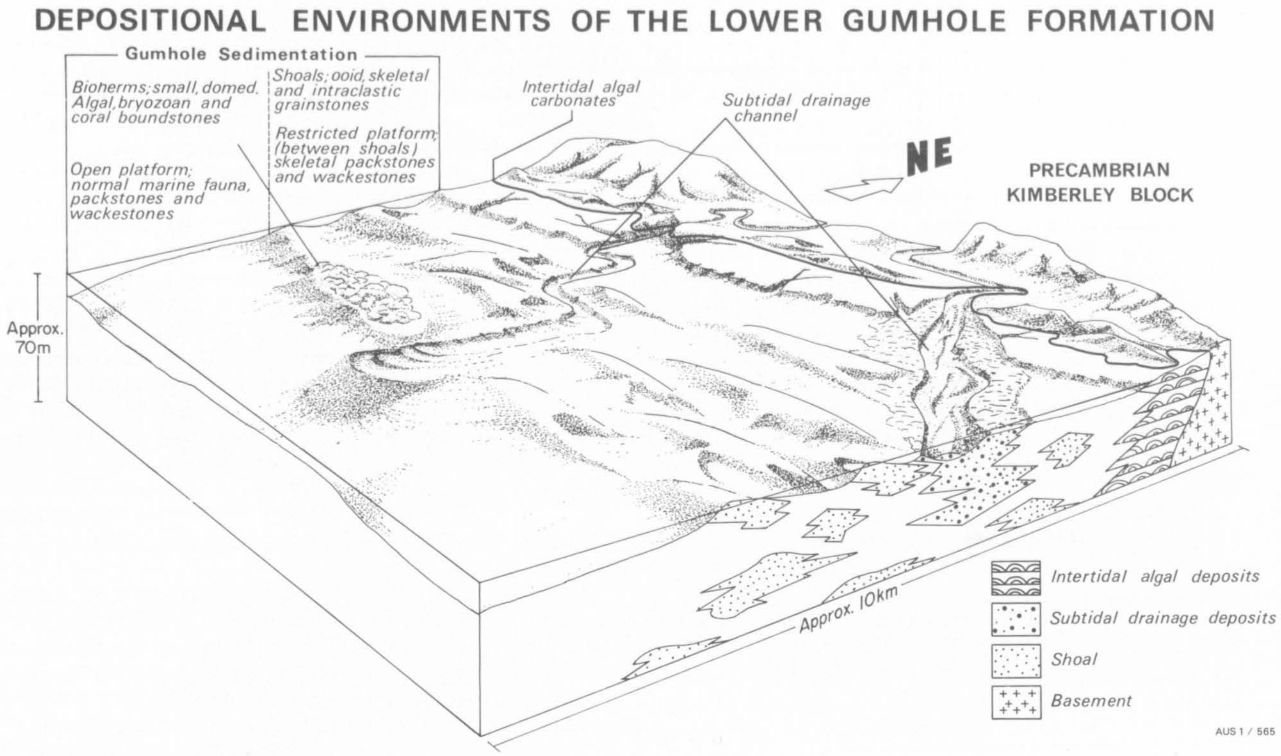

Figure 11. Depositional environments of the lower Gumhole Formation.

gressive and all facies were onlapping shorewards to the northeast. However in late Devonian times, facies movements were regressive with the intertidal algal flat environment no longer existing. Instead, a sandy facies of the Yellow Drum Sandstone prograded over the Gumhole sediments as illustrated in Figure 15.

YELLOW DRUM SANDSTONE (new name)

Definition

The Yellow Drum Sandstone is named after Yellow Drum Bore, 1 km north of the Great Northern Highway 25 km west-northwest of Fitzroy Crossing. The type section (WCB 004, Fig. 4) is on a low ridge 1 km northeast of Yellow Drum Bore (Fig. 12a). It is supplemented by core from BMR Noonkanbah No 4, which was spudded in at the top of the type section.

In the type section the unit comprises massive beds of calcareous sandstone and silty dolostone, with minor shale and dolomitic siltstone and rare thin limestone beds. The exposed section is 14 m thick, whereas the complementary drill hole penetrated 68.9 m of the unit.

The unit directly overlies the Gumhole Formation; no contact is exposed but a coarse calcareous sandstone containing fish remains and brachiopods lies in close proximity to the base of section WCB 004 and is considered to belong to the Gumhole Formation. BMR Noonkanbah 4 failed to penetrate any strata of the Gumhole Formation, but conodonts from the basal beds are identical to those found within the Gumhole Formation.

The upper part of the section is obscured by sand and no boundary contact with calcarenites of the Laurel Formation is exposed. Diagnostic fossils are rare; the few conodonts are not diagnostic of either latest Late Devonian or earliest Early Carboniferous. However the stratigraphic position of the unit between the late Famennian Gumhole Formation and early Tournaisian Laurel Formation indicates that the unit straddles the Devonian-Carboniferous boundary. This unit has not previously been recognized, although Thomas (1959) included sandstones in the basal part of his Laurel Formation which we would refer to the Yellow Drum Sandstone.

Areal Extent and Thickness

The Yellow Drum Sandstone is poorly exposed immediately southwest of the Oscar Range, in the region of Yellow Drum Bore. Minor outcrops, together with float, are present to the northwest along the fault which trends parallel to the front of the Oscar Range. The unit has considerable subsurface extent, and is recognizable in wells drilled in front of the Oscar and Napier Ranges (Fig. 1). It extends from the Lennard Shelf into the Fitzroy Trough, where it was penetrated in Yulleroo No. 1 between 3734 m and 3850 m.

The thickness at the type section is of the order of 70 m; comprising 14 m in outcrop, and 68.9 m in BMR Noonkanbah No. 4, which was spudded in near the top of the exposed section. A complementary drill hole to the northwest near Twelve Mile Bore (BMR Lennard River No. 1) penetrated 54 m of Yellow Drum Sandstone before intersecting a fault which brought probable Luluigui equivalent in contact with the Yellow Drum Sandstone. In BMR Noonkanbah No. 2, which is 8 km west-southwest of the type section in a line perpendicular to the basin margin, a total of 106 m of Yellow Drum Sandstone was penetrated. The greatest thickness seen is in Napier No. 1 Well where the interval of 333-660 m is referred to the Yellow Drum Sandstone. The thickness of the unit varies from less than 50 m at the margins to about 100 m towards the central part of the depositional area. However information is scant in the latter area, and no information was obtained from St George Range No. 1 or Grant Range No. 1.

LITHOLOGY

The dominant rock types are calcareous sandstone, silty dolostone, and dolomitic siltstone together with minor shale and limestone.

The sandstones are white to yellow-brown or grey, calcareous and quartzose, many are friable, having only sparse cementation; feldspathic and lithic grains are rare. The quartz sand grains are medium to coarse-grained and are well rounded. The thick sandstone beds are commonly cross-bedded and the foresets are emphasized by concentrations of detrital mica. The thin sandstones are interbedded with siltstone, shale and dolostone. In places they are sometimes ironstained from oxidation of disseminated pyrite.

The dolostones (Fig. 12c) are porous, medium to thick bedded, and are increasingly calcareous toward the top of the unit. They are greyish-yellow, light brown, light green or dark grey, and are either colour-laminated or homogenous; they contain a few calcite-filled vugs. Some brecciation has occurred near the base of the unit.

The shales are dark brown, green, or very dark grey, and are either colour-laminated or homogenous; these usually have a plastic consistency. The siltstones are brown or, rarely, greenish-yellow, are usually well indurated, and show limited bioturbation (Fig. 13c). The few limestones are peloidal grainstones often partly recrystallized and totally indurated.

PETROLOGY

Of the variety of rocks in the formation, the terrigenous sediments are generally poorly and variably indurated. The carbonate rocks have undergone significant diagenetic modification, including dolomitization and pressure solution.

Dolomitization

The dolostones are crystalline and usually contain siliciclastic silt or sand within a silt-size matrix of dolomite and calcite crystals.Any increased porosity results from the removal of interstitial calcite, hence the noncalcareous dolostones are usually very porous and friable. In several cases the dolomite is ferroan although the iron content varies proportionally with the amount of disseminated pyrite present. The colour and texture of the dolostones may be homogenous, mottled or laminated (Fig. 12b). Sediment textures and structures are preserved mainly as a result of variations of siliciclastic grain size and abundance, or colour.

The time of dolomitization is uncertain. Invariably the dolomite, whether as rock or matrix, is uniformly crystalline silt-size euhedra (Fig. 12c). When low-Mg calcite is present it is interstitial to the dolomite as anhedral, or rarely, subhedral crystals.

Original components of their relict fabrics are rarely observed and sedimentary structures when preserved, are within uniform dolomites.

This, and the absence of dolomite crystal-size variation, is more indicative of very early diagenetic or even syn-depositional dolomitization of the carbonates.

Pressure solution

Park & Schot (1968) classify stylolitization on geometric properties. This however has no direct relationship with the process or end result. Semeniuk (pers. comm.) proposes classification on the end member including stylolaminates (laminations resulting from pressure solution), stylobreccias (breccias from *in situ* solution), and styloclots (relict clasts or clots in a totally different altered lithology caused by extreme stylobrecciation).

In carbonates of the Yellow Drum Sandstone stylolites, breccias, nodular limestone and closely spaced irregular laminations are present, and are considered to be pressure-solution phenomena resulting from varying degrees of compaction and solution influenced by the original structures and textures of the host lithology.

Normal styolites are readily recognized, especially when separate and well spaced, in a homogeneous lithology (Fig. 12d), and may be in any attitude to the bedding, even perpendicular to it (Fig. 12b). However, once their frequency of occurrence is increased, they merge, bifurcate and crosscut each other to produce a stylobreccia. In the juxtaposition of more than one type of carbonate, the effect is more dramatic with a break-up of the more competent beds (Fig. 13a). In the dolostones, the dominant unit is the silt-size dolomite rhomb; this is surrounded by a more soluble calcite. Pressure solution may remove this calcite, and where this happens the macroscopic result is less obvious, except for zones and irregular changes of porosity and colour. The colour change is due to subsequent alteration of trace iron minerals producing different iron oxides (Fig. 13b).

When solution is effective in numerous parallel zones, laminations result from a concentration of insolubles, and have composition, colour and thickness variations similar to a normal sedimentary feature except for the microstyolitic lamina boundaries. It is debatable whether such a stylolamination (Fig. 12b) results from an originally homogenous impure carbonate or from the enhancement of an original lamination; the latter origin seems more probable. Here the problem of interpretation arises from observing pressure-solution phenomena, some totally independent of, and other probably considerably influenced by, the original sediment texture. The effects of volume loss from solution too, are speculative unless some original feature crosscut by the stylolite can be used for the assessment.

It is the authors' opinion that, in this case, a laminated sediment is the prerequisite to the formation of a stylolaminate; and that pressure solution modifies or intensifies this original fabric.

Four facies are recognized, within two of which subfacies are distinguished. The stratigraphic position and petrographic data of these facies are found in Appendix 1.

Facies A: Dolostones

The dolostones are subdivided into (i) laminated and (ii) massive, homogenous types.

Subfacies A (i): Laminated dolostone

This subfacies includes minor thin beds of dolomitic siltstone and dolomitic limestone.

The laminated calcareous dolostones are usually thin-bedded, but rarely they may be thick-bedded to massive. Alternations of light olive, blue, yellow-grey and yellow-brown colours give a striking lamination to the rock. The dolostone commonly contains 10-30 percent silt and clay; and have low intercrystalline porosities, variable in a mottled distribution (Fig. 13b). Some beds are more porous as a result of mesoscopic vertical and horizontal solution vugs which, in some cases are calcite-infilled. Algal oncolites and recrystallised ooids are infrequently discernible in the dolomitic limestone.

The thin bedded dolomitic siltstones comprise angular quartz and feldspar silt particles, with interstitial dolomite.

The origin or composition of the initial carbonate in this environment is conjectural. Prominent lamination in the dolostones suggests that the supply of sediment introduced was intermittent, whether produced by marine processes, floods or winds. Bioturbation is absent, suggesting that environmental conditions were adverse to fauna. If salinities were the controlling factor, they were not high enough for gypsum precipitation. The carbonate was possibly dolomitized soon after deposition. It is considered that the laminated dolostones are limited to both restricted intertidal and supratidal environments.

Subfacies A (ii): Homogeneous and mottled dolostones

This subfacies comprises thick and thin-bedded, rarely laminated, greyish yellow to light olive-grey dolostone. They contain 19-42 percent of angular silt and either very fine or rounded medium-grained sand, consisting of quartz, feldspar and quartzite fragments. The rock may be uniform, mottled, or laminated in colour. An increased porosity is commonly associated with the mottled areas. Bioturbation, produced by *Chondrites*, is better preserved in the few laminated beds. Laminae are distinguished by colour and sand content; some of them are undulose, eroded, curled or even encrusting, indicative of algal-mat origin. (Fig 13c).

Rare horizons of cross-stratified ooid grainstones containing a sparse fauna are usually recrystallized and partly dolomitized.

Pyrite is ubiquitous as disseminated, very fine cubes, which are limonitized and stain the dolomite.

Sedimentation of this subfacies, like subfacies A(i), was intermittent. The dolomites were probably originally laminated although this feature has since been partially or wholly destroyed by bioturbation during brief periods when normal marine conditions prevailed. Some laminated algal biota survived the grazing and were dessicated and reworked.

This subfacies is interpreted as a bioturbated upper intertidal-supratidal dolostone.

Facies B: Sandstones

Subfacies B(i): Cross-stratified well-sorted sandstone

This rock type is generally medium to thick-bedded, calcareous but friable. Colours range from pinkish grey to moderate and dark greenish grey. Interparticle porosity is good unless minor ferroan-poor calcite cement is present. Sand is dominantly fine to medium-grained, but in some cases there is a second mode of coarse or very coarse, subspherical, subangular grains composed of quartz, K-feldspar, chert and quartzite, with some biotite. The potash feldspars have large abraded syntaxial overgrowths, which indicate that the grains were reworked from an earlier marine sandstone. As a result of concentration and alignment on bedding surfaces, biotite flakes commonly delineate the cross-laminations. Lignitic flakes also occur in this way. The poorly lithified sandstones have dominantly straight-grain contacts which imply a history of moderate compaction.

Interbedded with the sandstone are thin beds of laminated siltstone which are generally bioturbated and mottled. Some thin beds of dark grey mud are homogeneous, apart from zones of vertical tubular fenestrae (Fig. 13d) which are terminated by the upper erosive surface of a sandstone.

No macrofossils have been observed in this subfacies.

These sandstones are considered to have been deposited in fluviatile or estuarine conditions, the sediments being derived from a sedimentary source area. The clean sands are commonly cross-stratified with adjacent dark silts and muds containing vertical tubular fenestrae. The muds had a high organic content which was preserved in reducing conditions until extensive bioturbation produced a mottled sediment texture. These fine sediments were probably stabilized by aquatic plants.

Subfacies B(ii): Poorly sorted laminated sandstone

This facies consists of thin to thick-bedded friable sandstone which is pale greyish yellow to greenish blue and bluish white. Internal lamination is defined by sand-size variations and colour. Imbricated mica flakes and green clay clasts are present within the laminae.

The sandstone is poorly sorted with grain size varying from fine to very coarse. The subspherical and subangular grains are quartz, feldspars with syntaxial overgrowths, siltstone and dolomite clasts. Chlorite, biotite and muscovite flakes also occur. Most grains are stressed and have straight intergrain contacts; some shattering of grains has occurred *in situ* and calcite replaces some quartz grains (Fig. 12f), implying high pressures and compaction. Some of the better sorted sandstone have optically continuous calcite in which there are relict chalcedonic vug infills (Fig 13f). Chalcedonic precipitation was probably on early carbonate cements which have since recrystallized to larger crystals. Disseminated pyrite is a minor constituent.

The depositional environment is interpreted as a floodplain. Dolomite and siltstone clasts were probably eroded from adjacent supratidal regions which may also have received floor deposits of silt. Bioturbation was rare and the sediment retained original lamination.

Facies C: Peloidal grainstone

These peloidal grainstones are interbedded with, and overlie subfacies B(i) and B(ii) in BMR Lennard River No. 1, and also define the base of the Laurel Formation as shown in Figure 14. Because of its transitional nature, this facies is common to both formations, but is dominant in the Laurel Formation where it will be discussed again.

Facies C consists of thin-bedded, sometimes laminated peloidal grainstones, which are light olive grey in colour but weather to a mottled pale greyish yellow; they are infrequently interbedded with minor amounts of siltstone and shale. The peloids vary in size, the larger forms being fenestrate mud lumps with angular stylolitic margins.

Apart from the abundant peloids, the grainstones have varying small amounts of silt and fine to coarse-grained sand, ooids, and skeletal fragments including small rounded lumps of the coralline algae *Parachaetetes*. Fragments of pelecypods, brachiopods and crinoids are abraded, while gastropods and ostracod shells are complete and infilled with spar. The mollusc fragments are recrystallized and can only be identified by their micritized margins.

The grainstones have zones of intense stylolitization around the margins of the grains and this results in a limited interparticle porosity. Dolomite and silt grains are concentrated in these compaction zones.

The thin bedded peloidal grainstones and interbedded fine siliciclastics are indicative of variable energy conditions. During quieter periods there was an accumulation of algal fenestrate carbonate muds which were grazed by gastropods and ostracods. The limited fauna and lack of bioturbation implies unfavourable conditions for an abundant marine fauna such as higher salinities. During more turbulent conditions, the mud was reworked into peloids, while siltstone and skeletal fragments, including coralline algae, were introduced from a more open-marine environment.

This facies represents a very shallow restricted marine or lagoonal environment.

Facies D: Interbedded sandstone, siltstone, limestone

This facies is present in both BMR Noonkanbah No. 4 and BMR Lennard River No. 1, as recurring units of approximately ten metre thickness.

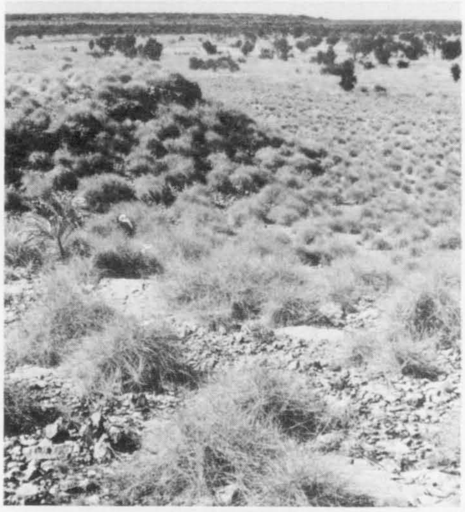

Figure 12a. Rubbly outcrop of fine-grained dolomite; Yellow Drum Sandstone, Yellow Drum Bore (locn WCB 004).

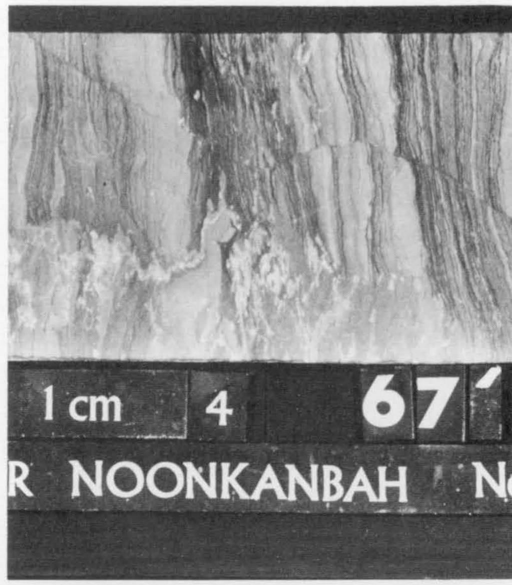

Figure 12b. Compacted laminated dolomitic siltstone with a high-angle fault and vertical stylolite; Yellow Drum Sandstone, BMR Noonkanbah 4 (locn WCB N4/67) x 0·7

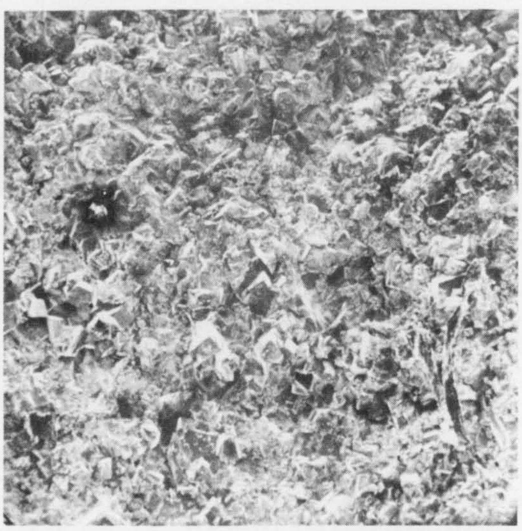

Figure 12c. Fine sucrosic dolomite with microporosity; Yellow Drum Sandstone, BMR Noonkanbah 4 (locn WCB N4/118), SEM photograph x 1000

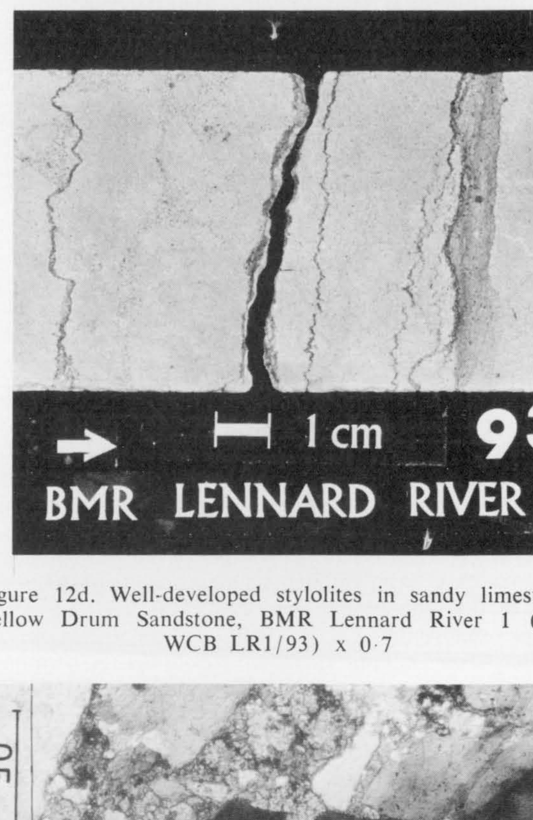

Figure 12d. Well-developed stylolites in sandy limestone; Yellow Drum Sandstone, BMR Lennard River 1 (locn WCB LR1/93) x 0·7

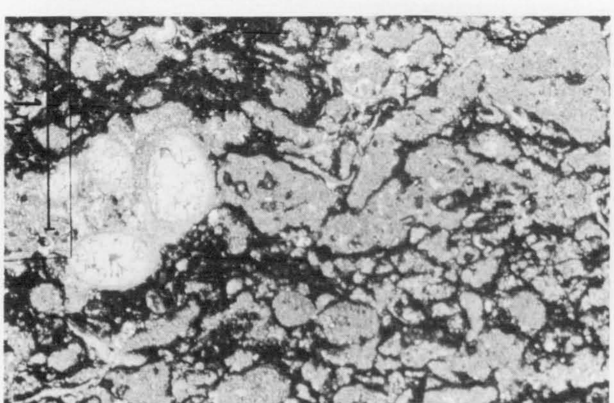

Figure 12e. Compacted pelletal limestone with undeformed spar-filled gastropod; Yellow Drum Sandstone (locn WCB 004/5).

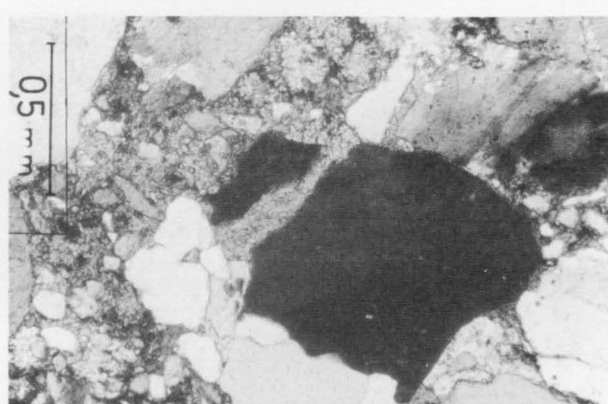

Figure 12f. Calcite replacing quartz in a quartzite fragment; Yellow Drum Sandstone, BMR Lennard River I (locn WCB LR1/107) x 58

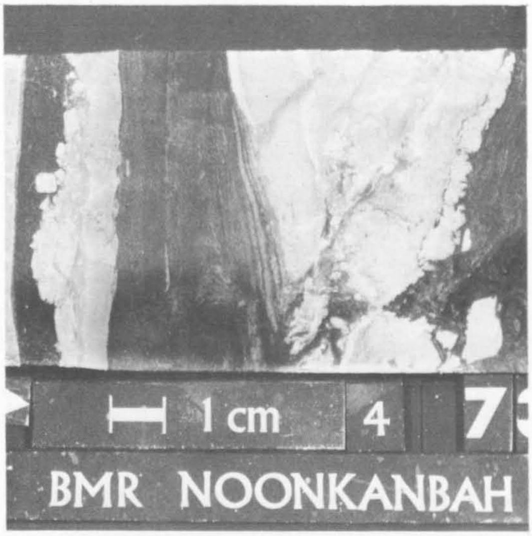

Figure 13a. Solution brecciation in dolomites and consequent disturbed laminae in the interbedded shales; Yellow Drum Sandstone, BMR Noonkanbah 4 (locn WCB N4/73) x 0·7

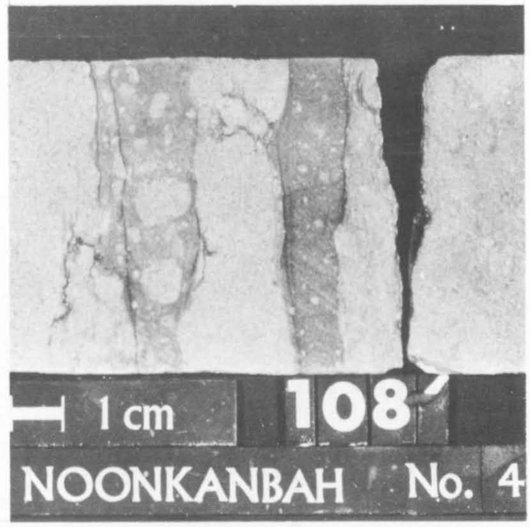

Figure 13b. Decalcification of impervious calcareous dolomites (dark bands) has produced pale porous dolomite patches which superficially resemble clasts; Yellow Drum Sandstone, BMR Noonkanbah 4 (locn WCB N4/108) x 0·7

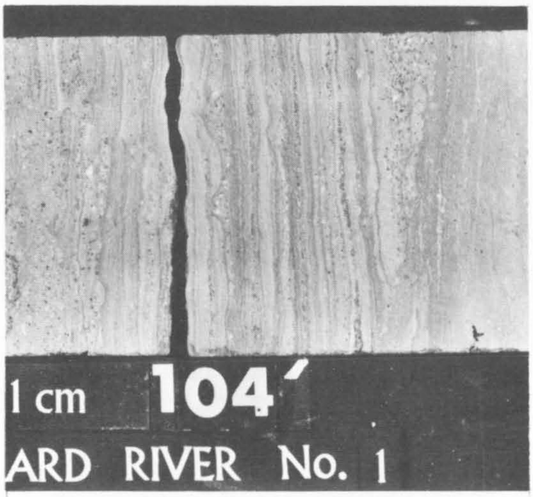

Figure 13c. Algal laminae in interlaminated dolomites, dolomitic quartz sandstones and siltstones; Yellow Drum Sandstone, BMR Lennard River 1 (locn WCB LR1/104) x 0·7

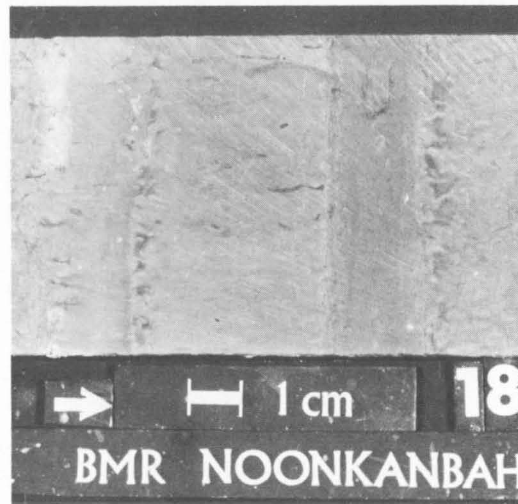

Figure 13d. Vertical tubular fenestrate of probable plant origin in calcareous siltstone; Yellow Drum Sandstone, BMR Noonkanbah 4 (locn WCB N4/182) x 0

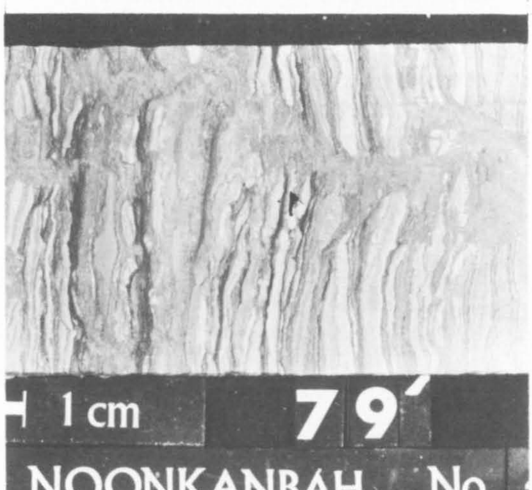

Figure 13e. Bioturbated (?) laminated dolomite and siltstone; Yellow Drum Sandstone, BMR Noonkanbah 4 (locn WCB N4/79).

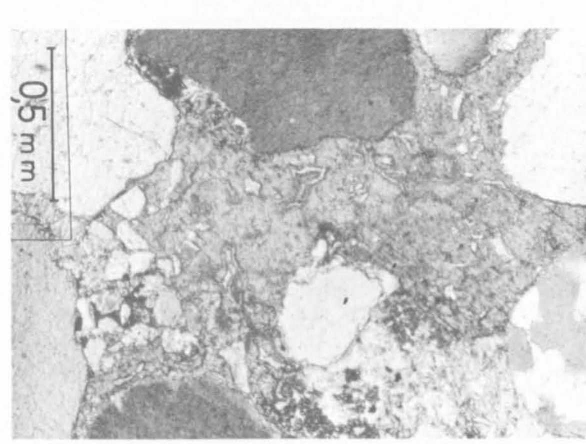

Figure 13f. Chalcedonic cement partly infilling minute solution vugs in a poikilitic calcite cement; Yellow Drum Sandstone, BMR Lennard River 1 (locn WCB LR1/107) x 58

Facies D consists of internally laminated sandstone, siltstone and dolomitic limestone. These rocks are intimately interbedded and lithological variations are generally gradational, as are the colours — light greenish grey and yellow to light olive grey, which are sometimes mottled.

The siltstones are in some cases clayey, or else partly indurated by fine dolomite or calcite cements. They are generally fissile; some silt-sand contacts exhibit load-casting. The terrigenous sediments are frequently bimodal, comprising subangular silt and fine sand, and spherical coarse sand 'floaters'. Some bioturbation has occurred, and a sparse fauna of crinoid fragments and fish plates is present.

The laminated and thin bedded lithologies indicate variable depositional energy conditions in an environment receiving infrequent marine incursions and fauna with resultant bioturbation. Discontinuous terrigenous deposition is considered to have occurred during river flooding over supratidal areas. Between floods and during infrequent marine incursions, carbonate accumulation and partial dolomitization occurred. The depositional environment is interpreted as supratidal flats.

Stratigraphic Relationships

The Yellow Drum Sandstone conformably overlies the Gumhole Formation. Nowhere in outcrop is a contact seen, but in BMR Noonkanbah No. 2 the contact is at 540 m. In the area of Yellow Drum Bore sandy calcarenites of the Gumhole Formation and fine-grained dolomites of the Yellow Drum Sandstone crop out in close proximity. BMR Noonkanbah No. 4 penetrated 70 m of Yellow Drum Sandstone, but failed to intersect any rock types referrable to the Gumhole Formation; also, the conodonts recovered suggest that the bottom of the hole is close to the boundary.

BMR Lennard River No. 1 penetrated 54 m of Yellow Drum Sandstone and then passed through a fault into probable Luluigui Formation equivalent. However, Yellow Drum Sandstone directly overlies the Gumhole Formation in May River No. 1, Langoora No. 1, Meda No. 1, Blackstone No. 1, Sister No. 1, Palm Spring No. 1, Napier No. 1 and possibly in Yulleroo No. 1. In Hawkstone Peak No. 1 it overlies late Fammennian birdseye limestone; this is the only known locality where the Yellow Drum Sandstone does not overlie the Gumhole Formation.

The Yellow Drum Sandstone is considered to be a supratidal and intertidal deposit, and as such probably interfingers with the open marine Gumhole Formation and also with the overlying Laurel Formation.

The relationship between the Laurel Formation and the Yellow Drum Sandstone is clearly seen in BMR Lennard River No. 1, which was spudded in near the base of the Laurel type section and intersected the contact at about 7 m. The boundary is drawn at the base of a sequence dominated by peloidal limestone, which corresponds to the top of a sequence dominated by sandstone.

Palaeontology and Age

The biota of the Yellow Drum Sandstone is greatly impoverished relative to the enclosing units. This is typified by the ostracods which are relatively abundant in the Laurel and Gumhole Formations, but which are absent in dolomitic limestone between 466 m and 521 m in BMR Noonkanbah No. 2. This is probably due to an unfavourable environment at the time of deposition of this interval (Jones *in* Veevers & Wells, 1961).

The flora is relatively diverse in the siltstone (Balme & Hassell, 1962); apart from the long-ranging species (see above under Gumhole Formation) the following also occur: *Verucosisporites* sp., *Reticulatisporites textilis* Balme & Hassell, *Convolutispora* sp., *Cincturasporites* sp. cf. *C. literatus* (Waltz), *Cincturasporites* sp., *Knoxisporites*? sp., *Cirratriradites*? sp., *Diaphanospora* sp., and *Endosporites*? sp., This group appears to be confined to the Yellow Drum Sandstone and suggests a sufficiently different spore assemblage for it to be diagnostic of this interval. The reason that Balme & Hassell left most of the flora in open nomenclature was because of low recovery of specimens. Two forms, *Verucosporites* sp. and *Reticulatisporites textilis* Balme & Hassell are known from BMR Noonkanbah No. 2 and the uppermost sample in Kimberley Downs 67 Mile Bore. This suggests that there may be a thin veneer of Yellow Drum Sandstone preserved beneath the Permian unconformity in the 67 Mile Bore area.

Balme & Hassell (1962) note that the spore asemblage, which is present in both the Gumhole Formation and Yellow Drum Sandstone, is comparable to a flora from the Famennian of the Don Valley in the USSR (Naumova, 1953). The Yellow Drum Sandstone flora is comparable to the flora which ranges from the Dankovsky up to the Khovansky, this latter unit is latest Late Devonian to earliest Carboniferous (Chizhova, 1976). Roberts *et al.* (1972) point out that *Leiozonotriletes naumovae* Balme & Hassell is considered to be a junior synonym of *Hymenozonotriletes lepidophytus* Kedo, which is a zone species of the Strunian (latest Late Devonian) of Belgium and is also known from Germany, North America and North Africa. The few conodonts are referred to species known from both the Gumhole and Laurel Formations and include *Pelekysgnathus australis* Nicoll & Druce (a multi-element species), *Clydagnathus cavusformis* Rhodes, Austin & Druce, *C. gilwernensis* Rhodes, Austin & Druce, *Hibbardella* cf. *H. insignis* Huddle, *H.* cf. *H.* (Cooper) *micra Neoprioniodus alatus* (Hinde), *Ozarkodina abnormis* (Branson & Mehl), O. *flexa, Polygnathus communis communis* Branson & Mehl, *P.* aff. *P. lacinatus* Huddle, *Prioniodina*? *symmetrica* Branson & Mehl, *Pseudopolygnathus* cf. *P. dentilineatus* E.R. Branson *Spathognathodus aciedentatus* E.R. Branson, *S. plumulus* Rhodes, Austin & Druce, *Synprioniodina regularis* E.R. Branson, gen et sp. indet. A, and a form similar to, but distinct from, *Polygnathus parapetus* Druce.

Pelekysgnathus australis is probably confined to the latest Late Devonian whereas *Clydagnathus cavusformis*, *C. gilwernensis*, and *Pseudopolygnathus* cf. *dentilineatus* are indicative of the earliest Early Carboniferous.

The occasional thin limestone beds yield occasional brachiopods, gastropods, ostracods and algae — which have not been identified.

The unit is diachronous and was deposited during the latest Devonian (doIV — tnIa) and earliest Carboniferous (tnIb). However the majority of the unit was deposited during the Strunian (tnIa); this interval also marked the greatest areal extent of this facies.

Geochemistry

Geochemical analyses were strongly biased to the carbonate beds which, being dolomitic have a relatively high Mg content (5.93%) and a Ca/Mg ratio of 2.6.

Both Ba and P are significantly low: the low P is probably due to the virtual absence of fish remains compared with contiguous formations. Mn also has low concentrations, which may indicate a more moist climate than that which pertained during the deposition of the Gumhole Formation; this may also account for the low Ba Content. Of the minor elements only Zn shows a departure from average concentrations, having a slightly higher mean value, although the cumulative frequency curves for Pb and Zn suggest the presence of two populations (Druce & Radke, 1977).

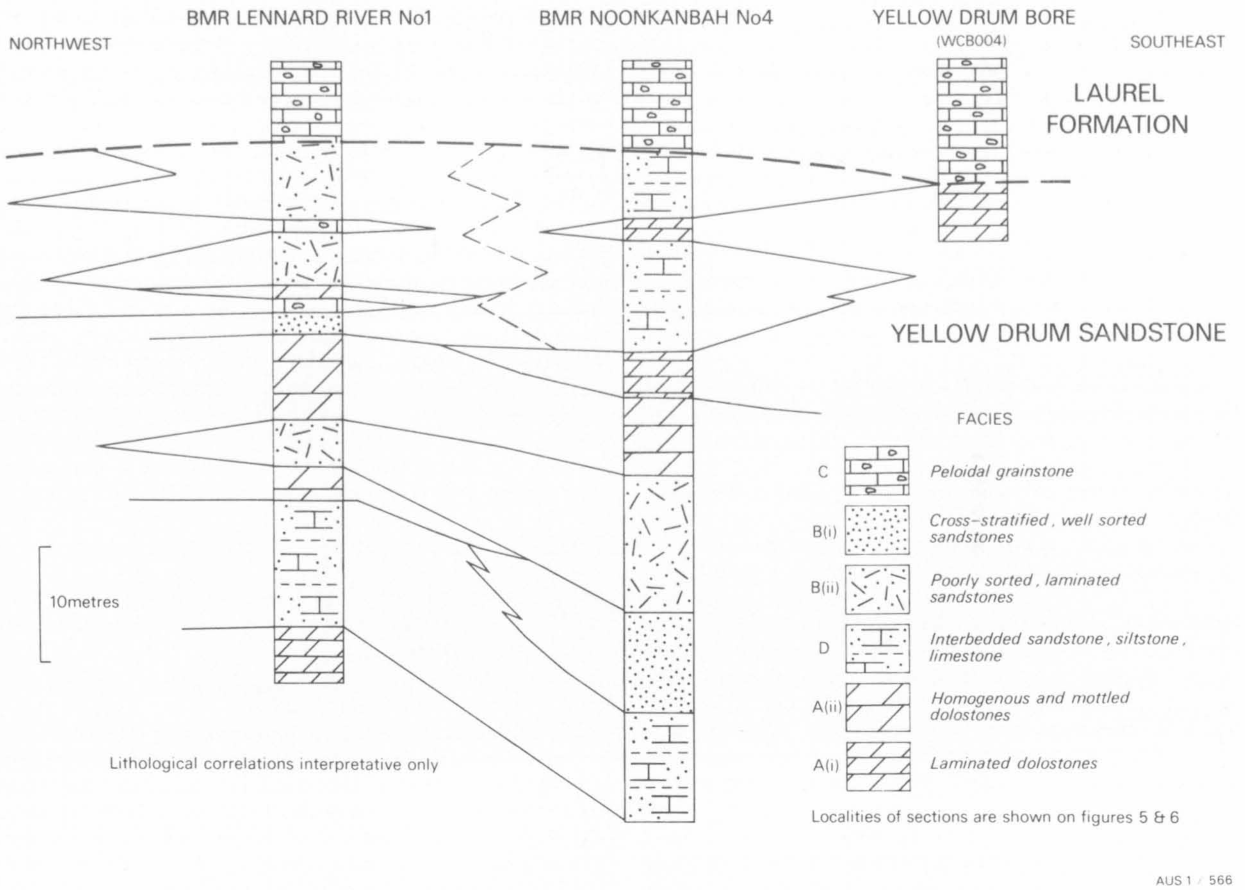

Figure 14. Regional variation of environments, Yellow Drum Sandstone.

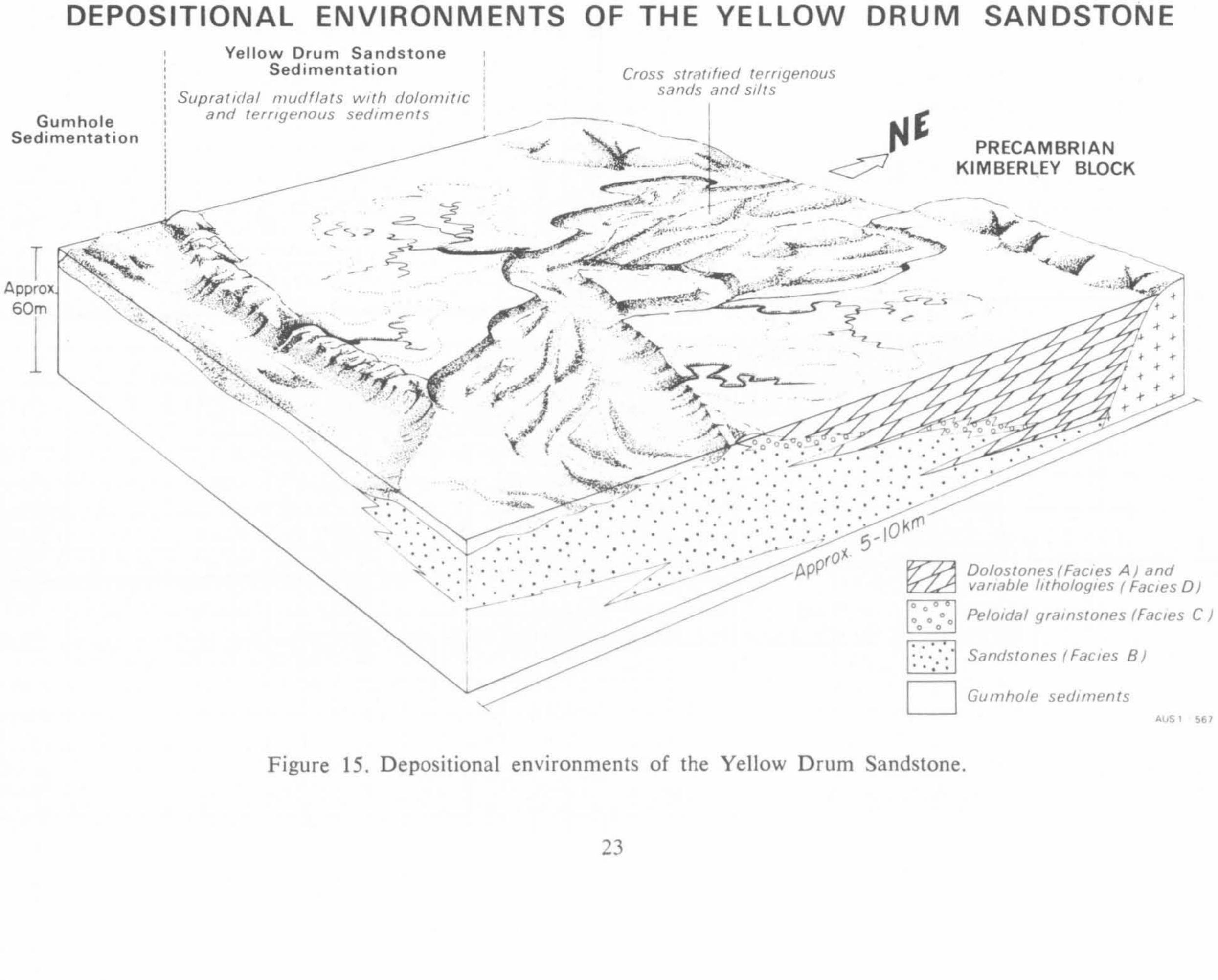

Figure 15. Depositional environments of the Yellow Drum Sandstone.

Depositional History

It is apparent from the sequence of facies observed in the well and surface sections (Fig. 14) that the depositional history of the Yellow Drum Sandstone in any one section was variable. Although there are limitations in determining facies distribution from only three sections, we make the following generalizations: dominant deposition was intermittent throughout the sequence; earlier carbonates are mostly dolostones and only towards the top of the formation are limestones dominant; terrigenous sedimentation produced two bodies of sediment separated by dolomitic facies. Each body of terrigenous sediment comprises all three terrigenous facies.

Sedimentation was in marine subtidal to supratidal and fluvial environments, and during the initial phase the marine subtidal environments were those forming the Gumhole Formation. These environments were directly controlled by variations in tidal ranges, tidal currents and floods.

The spatial relationships between depositional environments of these facies are illustrated in Figure 15. On the broad coastal flat there were infrequent marine and fresh-water inundations. During brief submergence laminated dolostones were formed in small areas; where the marine flooding was more frequent, a significant fauna survived and bioturbation of the supratidal dolostones resulted. The intermittent flooding from land drainage superimposed terrigenous sedimentation on both sequences, and this too was subjected to brief or extended marine innundations.

Over this supratidal flat fluvial channels with extensive and intricate drainage patterns transported the terrigenous sediments across all supratidal environments. Estuarine conditions developed at the channel mouths where the introduced sediments were more extensively reworked than in the fluvial environments. Intertidal flats lined the margin of the supratidal zone with the Gumhole Formation sedimentation and later transitional with Laurel environments as well.

In summary, the Yellow Drum Sandstone is a regressive unit characterized by sandstone and dolostone bodies that prograded over the shallow marine Gumhole Formation to develop a broad supratidal tract.

LAUREL FORMATION

Areal Extent and Thickness

The Laurel Formation crops out in a belt 2-10 km wide southwest of the Napier and Oscar Ranges; the best exposures are in the area of Twelve Mile Bore (Fig. 4), where Thomas (1959) chose his two complementary type sections. In the subsurface the unit extends along the Lennard Shelf, and into the Fitzroy Trough. BMR Noonkanbah No. 2 was drilled 22 km from the type section, towards the trough, and penetrated 357 m of Laurel Formation in the interval 76 m — 433 m, of which the upper 168 m is dominantly shale. The lower, more calcareous, part of the sequence is thus 189 m thick in BMR Noonkanbah No. 2 compared with the 455 m estimated by Thomas (1957) in the Twelve Mile Bore area from poor surface outcrop, and 386 m measured by us. The thickness in BMR Noonkanbah No. 2 is probably a more realistic figure than either of the thicknesses measured from surface outcrop.

In the subsurface the limestone member thickens from less than 50 m near the northerly margin to over 150 m towards the centre of the depositional area; greatest thicknesses measured are 189 m in BMR Noonkanbah No. 2, 158 m in Langoora No. 1 and 151 m in Lake Betty No. 1.

The overlying shale member ranges in thickness from zero on the northerly margin to 649 m in Lake Betty No. 1. The southeasterly part of the trough was the main depositional focus, whereas in the Napier area the unit is relatively thin with average thicknesses of between 50 and 100 m.

Lithology

The sequence comprises interbedded limestone, shale, siltstone, sandstone and minor dolomite. In outcrop the limestones are well bedded, but laterally discontinuous; white, weathering to yellow and light brown; and are mainly skeletal grainstones (figs. 17c-e). In the subsurface they are of two types: brown, bituminous, bioturbated, shaly, bioclastic limestone, and white to light brown and light yellow sandy bioclastic and intraclastic limestone. The unit is dominated in its lower part by limestones, whereas in the upper part the dominant rock type is grey calcareous shale (seen in BMR Noonkanbah No. 2). These are recognised as two distinct, but unnamed, members.

Petrology

Two facies are recognized within the Laurel Formation: facies A — limestones; and facies B — siltstone, shale and bioclastic limestone.

Facies A: Limestones

Six subfacies are differentiated within the limestones, all of which have a bioclastic component and are mostly grainstones. Subfacies differentiation has been based on three criteria: the relative abundance of skeletal components and their mode of preservation; the siliciclastic component of the limestone; and the relative abundance and types of siliciclastics interbedded with the limestone.

Little emphasis was placed on bedding and sedimentary structures as there was insufficient data available because of the poor exposures.

The lithologies of this sequence are tabulated in Appendix 1.

Subfacies A(i): Peloidal grainstone

This subfacies forms the base of the Laurel Formation and, as has already been noted, interfingers with the upper Yellow Drum Sandstone.

The facies comprises buff, and some white to pink peloidal grainstones containing minor quartz silt. These limestones are slightly recrystallised, and at the base of the facies, dolomitised as well. Significant features include encrustations, boring, and micritizing and pelletizing effects.

Some of the silty limestones are nodular; remnant blocks of limestone that survive solution are preserved as nodules within a residual siliciclastic that compacted around them (Fig. 16b).

Irregular and rounded peloids of fine to medium-grained sand size are the dominant grain type. Only rarely do they have an internal fabric, although some are micritized ooids in which the laminae are partly preserved. Also present are abraded lithoclasts of peloidal grainstones, skeletal grains, and mud lumps which incorporate skeletal fragments. Abraded, micritized pelecypod fragments bored by algae, together with mud-coated crinoid ossicles and complete thin shelled ostracods are the most abundant skeletal grains. Some abraded brachiopod, as well as encrusting and fenestrate bryozoan fragments and calcareous algae, also occur. *Umbella* and calcispheres are well preserved.

Peloids resulted from algal boring and micritization of allochems, especially ooids. Similar effects are known from recent sediments (Bathurst, 1971, p. 389). These peloidal grainstones are considered to have accumulated in a moderately shallow turbulent environment above wave base in which muds were winnowed away and reworking of indurated peloidal sediment was possible.

The presence of *Umbella*, calcispheres, and coralline algal fragments, and the absence of fish fragments, imply a flourishing algal flora in conditions adverse to fish habitation. This was probably in a hypersaline environment into which abraded skeletal fragments were transported from a normal marine area. Such a restricted hypersaline environment may have been due to embayment in a lagoon or a hydrodynamically stabilized salinocline on an open shelf.

Subfacies A(ii): Crinoidal grainstone

The subfacies consists of medium-bedded, grey or sometimes buff grainstones that have a dominance of crinoid bioclasts. The facies contains angular quartz; silty at the base but becoming coarser towards the top. It overlies the basal peloidal grainstone facies in the type section (WCB 101). Gaps within the outcropping sequence may represent weathered siltstone.

The dominant grains are crinoid ossicles and spines which are not abraded but are mud-coated. Internally they have finely disseminated pyrite in the pore-filling syntaxial cement. Other bioclasts include mud-coated abraded brachiopod fragments and pelecypods with occasional complete ostracods, gastrocods, fish fragments and calcareous algae. Some vertical burrows are poorly preserved.

Low to moderate energy conditions probably prevailed with localized winnowing and redeposition of the finer terrigenous material, producing grainstone shoals and intershoal silts. The dominant, non-abraded crinoid pieces and transported pelecypod and brachiopod fragments were mud-coated and reworked from the local muddy environments. Restricted marine conditions prevailed, resulting in an impoverished fauna, but these conditions were suitable for fish habitation and limited bioturbation.

A restricted platform and shoal environment is interpreted from the subfacies.

Subfacies A (iii): Brachiopod grainstones and packstones

Subfacies A (iii) comprises medium-bedded, buff grainstones and packstones. The interbedded recessive rock type not exposed in outcrop is probably poorly lithified siltstone. This subfacies occurs in the upper type section (WCB103).

Brachiopods are the dominant bioclasts, preserved as single valves with algal boring, abraded fragments and spines. Crinoid ossicles and complete ostracods are common, while gastropods, fish plates, foraminifera and abraded micritized pelecypod fragments have a limited occurrence. The limestones contain minor amounts of angular quartzose and very fine-grained sand. Considerable solution during early diagenesis was followed by cementation (ferroan-rich calcite). Calcrete replacement and formation is prevalent at the surface and most limestones have been partially recrystallized and micritised at the surface.

These features probably reflect a quiet, shallow and subtidal environment. The fauna was not diverse, yet dominated by brachiopods which probably lived on a muddy substrate — as inferred from the numerous productid spines in the limestone. A few crinoids, ostracods, foraminifers and fish lived in these conditions. Both the intense algal boring of the brachiopods and early solution probably reflects extremely shallow conditions, perhaps even involving intertidal emergence.

A restricted platform area of deposition is interpreted from this evidence.

Subfacies A(iv): Brachiopod-crinoid-ostracod grainstones

This subfacies consists of medium-bedded buff to white skeletal grainstones. It is present in the upper Laurel type section (WCB103).

Spines and thin abraded valves of brachiopods, crinoid ossicles and spines, complete ostracods and abraded pelecypod fragments are the essential components, with some gastropods, fish fragments and rare foraminiferans and bryozoans. These limestones have a minor sand content increasing in size upwards from very fine to coarse. Following early diagenetic solution and cementation by ferroan calcite, the limestones were moderately recrystallised, this in cases being micritisation.

Pelecypod fragments were apparently either transported into, or reworked within, the environment to produce the shell disintegration observed. The diverse fauna, dominated by brachiopods, is indicative of a normal marine environment.

Deposition is considered to have been in an intershoal environment of moderate energy in which sufficient agitation winnowed the finer sediment fraction from the carbonates.

Subfacies A(v): Sandy pelecypod skeletal grainstones

These grainstones are thin to thick bedded and white, light grey or buff. Interbedded with them are some packstones, calcareous shale, and very fine to coarse-grained sandstone.

This subfacies occurs in the upper part of the type section, specifically in WCB103 section and BMR Lennard River No. 2.

The limestones have a variable sand content. Abraded pelecypod fragments bored and encrusted by algae are dominant, supplemented by complete ostracods, cryptophyllids (Fig. 16e), crinoid ossicles and spines, gastropods and a few foraminiferans. These carbonates have been recrystallized.

The dominant sediment, of coarse terrigenous sand and abraded pelecypod fragments, must have resulted from continual winnowing and reworking, the presence of algal boring and encrustation implying shallow water, perhaps intertidal conditions.

The presence of such a number of diverse sediment types must reflect an environment with changing wave or current strength. It is deduced that this subfacies was deposited in a shallow water shoal and intershoal situation.

Subfacies A(vi): Silty brachiopod skeletal grainstones

These limestones are hard, medium to thin bedded, and white or mottled light pinkish grey to very pale orange. Dark yellowish orange shales and siltstone, or brown calcareous cross-stratified sandstones are interbedded with the limestones which may be laminated adjacent to the fine siliciclastics.

This subfacies recurs three times in the Laurel type section (in sections WCB101, 103 and BMR Lennard River No. 2).

The bioclastic limestone has ubiquitous brachiopod fragments which are abraded and frequently have algal borings on their outer surfaces; and productid spines, abraded ostracod valves, and crinoid ossicles and spines containing disseminated pyrite in their internal pores. Minor constituents include abraded pelecypod fragments, silt-size peloids, gastropods, encrusting bryozoa, fish fragments, calcareous algae, cryptophyllids and foraminiferans (Fig. 16d). In the laminated horizons, some bioturbation is apparent. The limestones have been compacted and recrystallised.

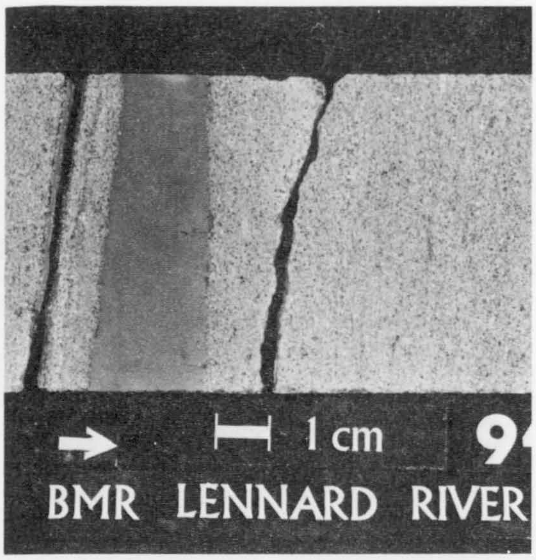

Figure 16a. Ooid sandstone with shale interbed; Yellow Drum Sandstone, BMR Lennard River 1 (locn WCB LR1/94).

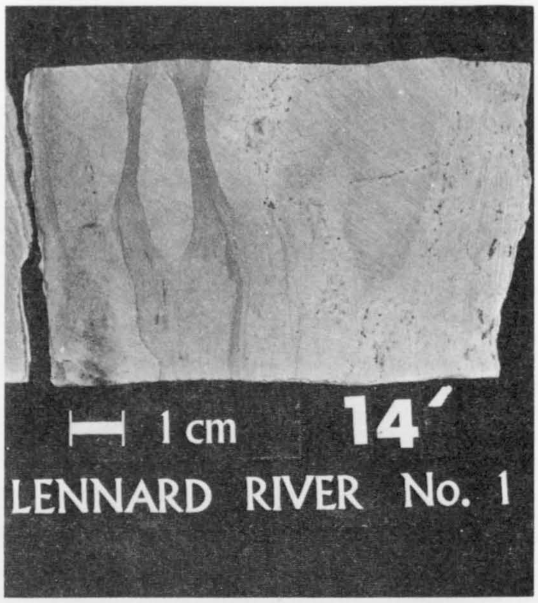

Figure 16b. Relict lenses of silty pelletal grainstone after pressure solution of the siltier horizons; Laurel Formation, BMR Lennard River 1 (locn WCB LR1/14).

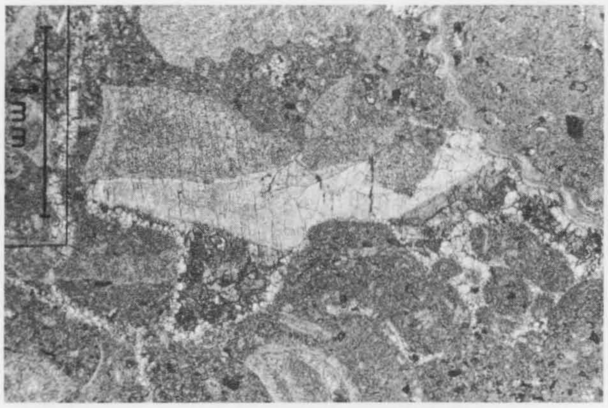

Figure 16c. Solution vugs in a skeletal packstone lined with ferroan-poor calcite druse—large syntaxial overgrowths extend from crinoids into the vug, which is filled with ferroan calcite; Gumhole Formation, type section (locn WCB 202/12) x 37

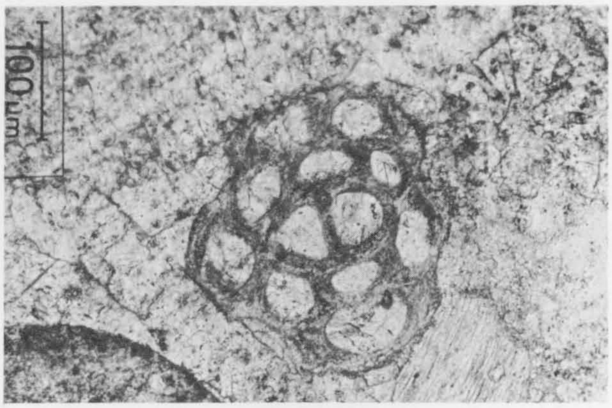

Figure 16d. Probable endothyrid foraminiferan; Laurel Formation, type section (locn WCB 101/59) x 230

Figure 16e. Cryptophyllid valves in longitudinal section—note the diagnostic growth lamellae; Laurel Formation, BMR Lennard River 2 (locn WCB LR2/127) x 45

Figure 16f. Syntaxial cement rim extending from crinoid ossicle on a skeletal grainstone; Laurel Formation, type section (locn WCB 102/1) x 58

Figure 17a. Trend lines of limestone beds with wavy gilgai (patterned ground) overlying subcrop—tree covered areas comprise Permian Grant Formation; Laurel Formation, 4·5 km southeast of Twelve Mile Bore.

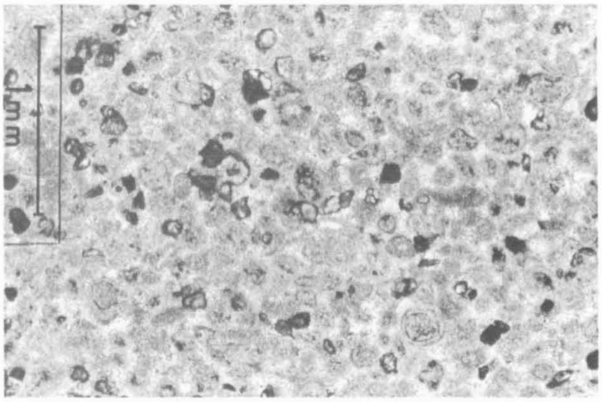

Figure 17b. Pelletal grainstone; Laurel Formation, type section I (locn WCB 101/2).

Figure 17c. Skeletal grainstone with ostracods; Laurel Formation, type section II (locn WCB 102/5).

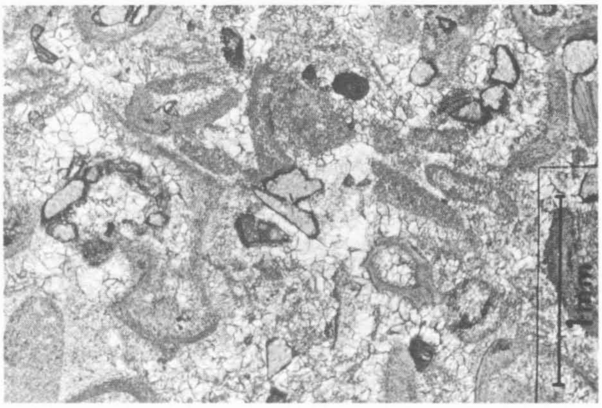

Figure 17d. Partly recrystallized skeletal grainstone; Laurel Formation. BMR Lennard River 2 (locn WCB LR2/127).

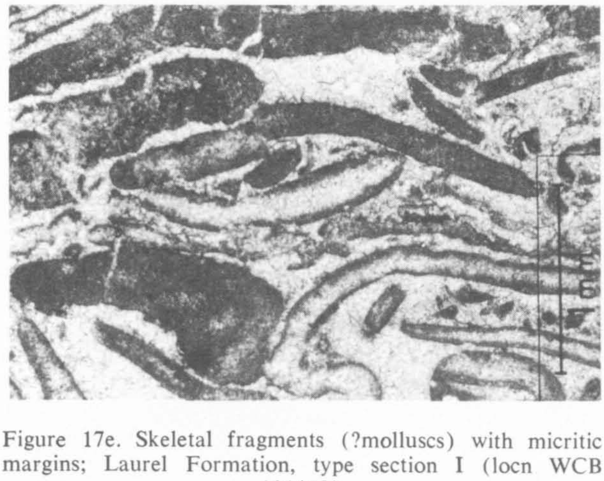

Figure 17e. Skeletal fragments (?molluscs) with micritic margins; Laurel Formation, type section I (locn WCB 101/18).

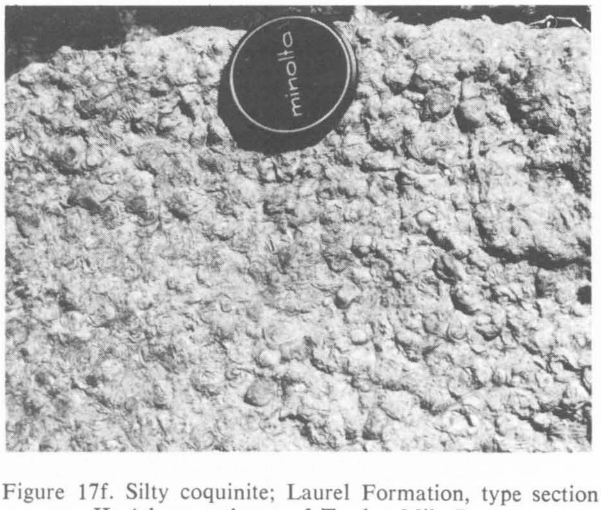

Figure 17f. Silty coquinite; Laurel Formation, type section II, 4 km southeast of Twelve Mile Bore.

The medium and thinly bedded grainstones have a characteristic high-energy shallow-water indicator, the abraded brachiopod fragments with dense algal borings. Reworking of this material was considerable but other skeletal contributions, namely productid spines, ostracods and cryptophyllids are more likely to have been derived from deeper water. These were rapidly buried. Overall, the fauna is very diverse, supporting evidence of shallow open-marine conditions. The interbedded siliciclastics are bioturbated and contain an equally rich fauna of cryptophyllids and brachiopods.

Deposition of this subfacies was in a shoal and open platform environment.

Facies B: Siltstone, shale, and bioclastic limestone

Facies B comprises thin beds and laminae of light to dark olive-grey calcareous siltstone, fissile olive-grey shale, and light grey to yellowish brown bioclastic grainstones. The facies is present in both the middle (section WCB102) and upper (BMR Lennard River No. 2) parts of the Laurel type section (Fig. 18). A significant proportion of the grainstones are characterized by a high silt content (up to 20%). *Umbella* and foraminiferans are absent in the siltier limestones. The main skeletal components are well preserved and comprise crinoid ossicles and spines, together with ostracods, cryptophyllids, encrusting bryozoa and small fasciculate *Syringopora* colonies.

At the base and top of the facies thick vertical burrows are present, ostracods show some abrasion, and abraded, angular fragments of brachiopods, molluscs and fish are also present. Stylolitization is more common in these zones.

The calcareous siltstone and mudstone contain an abundant, diverse fauna including the *Syringopora* colonies. During brief periods of increased turbulence, silty grainstones were produced.

Deposition of this facies was in a marine, open platform environment with generally quiet conditions prevailing.

Diagenesis

A generalized sequence of diagenetic events common to most limestones in the Laurel Formation is:

1) pyrite precipitation — most evident in internal pores of crinoid ossicles (where present it prevented the development of syntaxial rims)
2) cementation by acicular, ferroan-poor calcites. Where this did not occur, early compaction was enhanced.
3) compaction and solution occurring mainly within the cements (solution vugs were developed)
4) the infilling of vugs and pores by blocky, ferroan-poor calcite cement
5) stylolitic compaction, most abundant in the siltier zones
6) recrystallization of some limestones, often producing both enlarged and diminished grain fabrics within the one limestone. When recrystallized, cement fabrics were enlarged and allochems were micritized.

The diagenetic history is less complex, but generally similar to that of the Gumhole, noticeable differences being:

1) the absence of an early solution phase
2) widespread recrystallization
3) variations of ferroan content in single cement phases
4) the dominance of non-ferroan calcite cements.

This latter factor accounts for the lower iron and associated manganese levels in the Laurel limestones (Radke, 1976; Druce & Radke, 1977). An exception to this is in the limestone facies B where similarities in solution phases, dominant ferroan calcite cement, colour and weathering features exist with Gumhole bioclastic grainstones.

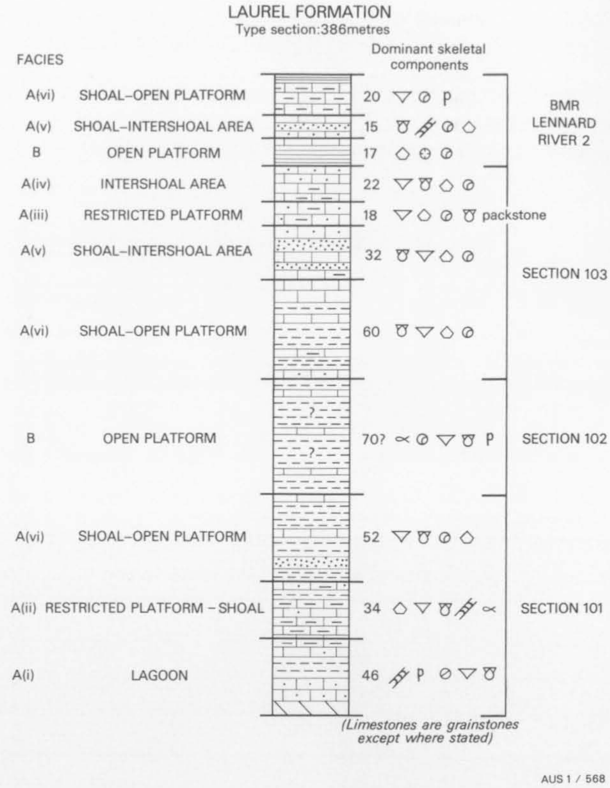

Figure 18. Interpretation of facies of the Laurel Formation type section.

Stratigraphic Relationships

The Laurel Formation conformably overlies the Yellow Drum Sandstone. BMR Lennard River No. 1 spudded in near the base of Type Section I of the Laurel Formation and intersected the lower boundary at 7 m. The facies interpretation of the Laurel Formation and the Yellow Drum Sandstone suggests that they could be laterally equivalent and thus that the units probably interfinger.

In the outcrop area the Laurel Formation is unconformably overlain by conglomerates of the Grant Formation, considered to be of Permian age but possibly as old as Late Carboniferous. However, in the subsurface the Laurel Formation is conformably overlain by sandstones of the Anderson Formation, which probably indicates a regressive phase.

Palaeontology and Age

The Laurel Formation contains a rich and varied biota including algae, brachiopods, bryozoans, conodonts, corals, fish, pelecypods, nautiloids, ammonoids, ostracods and microflora. The algae consist of well-abraded sand-sized coralline algae which are present in the lagoonal facies at the base of the unit. Some better preserved fragments are idenitifiable as the solenoporid *Parachaetetes*, and possible dasyclads *Orthriosiphon* and *Ivanovia*.

The brachiopods have been described by Veevers (1959b), and Thomas (1971); additional information is provided by Roberts (1971). The fauna consists of typical Lower Carboniferous forms including *Rhipidomella micheline*? (Leveille)*, *Schuchertella*? *dorsiplana* Thomas, *Schellwienella* sp. cf. *S. minilyensis* Thomas*, *Rugosochonetes*? sp. A, *Unispirifer fluctuosus* (Glenister)*, *Prospira laurelensis* Thomas*, *Spirifidina* gen. et sp. indet. Thomas, *Punctospirifer plicatosulcatus* Glenister*, *Ovatia* sp.*, *Cleiothyrdina minilya* Thomas*, *Cleiothyridina* ? *fitzroyensis* Thomas, *Composita hendersoni* Thomas, and *Grammorynchus eganensis* (Veevers). Thomas considers this fauna to indicate a Middle Tournaisian age; seven species (marked*) are common to the Laurel Formation and the Moogooree Limestone of the Carnarvon Basin.

Roberts (1971) described the brachiopod faunas from the Devonian and Lower Carboniferous of the Bonaparte Gulf Basin, and also considered material collected by him from the Canning Basin. In addition to the above fauna he identified *Acanthocosta teicherti* Roberts, *Rugosochonetes obtectus* Roberts, *Schuchertella* sp., *Magnumbonella prolata* Roberts, *Schizophoria* sp. cf. *S. resupinata* (Martin) *Marginata mimica* Roberts, *Protoniella*? *waggonensis* Roberts, and *Spinaurus cristata* Roberts. Based on this fauna he recognized a sequence of zones in the Laurel Formation corresponding to zones erected by him (1971) in the Bonaparte Gulf Basin and extending from the *Acanthocosta teicherti* Zone up to the *Septemirostellum ananicum* Zone. Roberts considers that this broadly equates with the K zone of Britain, essentially lower to middle Tournaisian.

Bryozoans have been noted by Thomas (1959), and Radke (1976); they are mainly of the encrusting type, but have not been studied in detail.

Conodonts have been noted by Glenister (1960), Thomas (1962), Roberts & Veevers (1971), Roberts et al. (1972); a few specimens have been described by Glenister & Klapper (1966), and a detailed study has been completed (Nicoll & Druce, in prep.). The fauna includes *Anchignathodus cristulus* (Youngquist & Miller), *Angulodus compressa* Huddle, *A. pergracilis* (Ulrich & Bassler), *Clydagnathus cavusformis* Rhodes, Austin & Druce, *C. gilwernensis* Rhodes, Austin & Druce, *Dinodus* sp., *Gnathodus* sp., *Hibbardella* cf.*H. insignis* Huddle, *H.* cf. *H. micra* (Cooper), *Hindeodella acuta* Branson & Mehl, *H. brevis* Branson & Mehl, *H. corpulenta* Branson & Mehl, *Ligonodina platys* Cooper, *Neoprioniodus* cf. *N. alatoides* (Cooper), *N. alatus* (Hinde), *N. barbatus* (Branson & Mehl), *Ozarkodina flexa* (Branson & Mehl), *O.* cf. *O. plana* Branson & Mehl, *Polygnathus communis* s.s. Branson & Mehl, *P. inornatus* Branson & Mehl, *Prioniodina*? *symmetrica* (Branson & Mehl), *Pseudopolygnathus* cf. *P. dentilineatus* E.R. Branson, *P. multistriatus* (Mehl & Thomas), P. cf. *P. nodomarginatus* (E.R. Branson), *Siphonodella* cf. *S. cooperi hassi* Thompson & Fellows, *Spathognathodus aculeatus* Branson & Mehl, *S. canningensis* Nicoll & Druce, *S. crassidentatus* (Branson & Mehl), *S. plumulus* Rhodes, Austin & Druce, *S.* cf. *S. robustus* (Branson & Mehl), *S. sulciferus* (Branson & Mehl) and *Synprioniodina regularis*.

Corals are rare in the Laurel Formation and most specimens, referrable to *Syringopora*,*Bothrophyllum* and cf. *Michelinia* (Hill *fide* Thomas, 1959), occur near the base of the unit.

Fish remains are relatively abundant, and bradyodont and cladodont shark teeth have been recorded by Thomas (1959, 1962). G.C. Young (pers. comm.) has identified acanthodian spines, including *Gyracanthus*, from the extensive collections made by us.

Pelecypods are not abundant but include cf.*Allorisma* and schizodont forms; gastropods are abundant and include *Straparollus*? *Murchisonia*? *Bucanopsis* and bellerophontids (Dickiens *fide* Thomas, 1962). Straight nautiloids are present but have not been described. A single ammonoid has been found; initially it was identified as *Imitoceras rotatorium* (de Koninck) by Glenister (1960) but he now considers it a new genus of the Imitoceratidae (*fide* Playford & Lowry, 1966).

Ostracods are abundant in certain beds within the Laurel Formation. They have been reported by Jones (1959, 1961, and *in* Thomas, 1959) but the fauna still awaits systematic

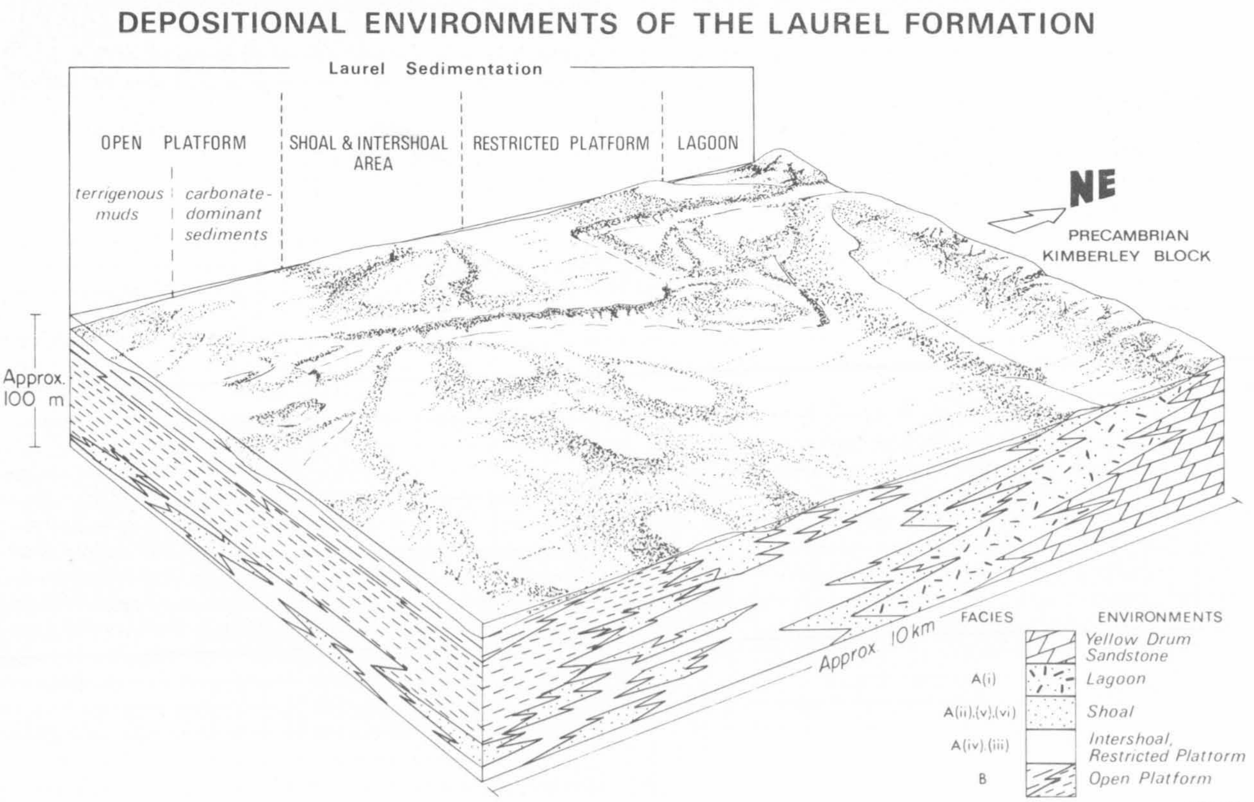

Figure 19. Depositional environments of the Laurel Formation.

description. However Jones (pers. comm.) provisionally recognises the following genera: *Bairdia*, *Cavellina*, *Leviella*, *Microcheilinella* (probably *obesa* Cooper), the Paraparchitidae *Shishaella* and *Shivaella*,? *Tetratylus*, *Bairdiacypris*, *Coryellina*, *Knoxiella*, *Silenites*, *Pseudochilina*, *Acratia*, *Cyathus*,*Evlanovia*, *Glyptopleurites*, *Graphiadactyllis*, and *Mernerites*. Also present is the cryptophyllid *Cryptophyllus diatropus* Jones.

The systematics of the microflora have not been published but resumés have been published by Balme (1960, 1964); Balme & Hassell (1962) have tabulated the Devonian forms which occur in the Laurel Formation. Two distinct floras are present in the Laurel Formation in the intervals 274-278 m and 76-79 m in BMR Noonkanbah No. 2. The lower flora consists of *Aurospora*, *Punctatisporites**, *Cyclogranisporites**, cf. *Reticulatisporites*, *Grandispora**, *Gravisporites*, *Petusotriletes**, and *Archaeozonotriletes**. Those genera marked with an asterisk also occur in the upper flora together with *Lycospora*, *Leiotriletes*, *Endosporites*, and *Apiculatisporites*.

The following species range from the Gumhole Formation into the Laurel Formation; *Leiotriletes pulvereus* (Balme & Hassell), *Calamospora microrugosa* (Ibrahim), *Granulatisporites frustulentus* (Balme & Hassell), *Retusotriletes* cf. *R. famenensis* Naumova, *Convolutispora fromensis* (Balme & Hassell), *Reticulatisporites ancoralis* (Balme & Hassell), *Cincturasporites* cf. *C. literatus* (Waltz), *Leiozonotriletes laurelensis* (Balme & Hassell), and *Diaphanospore riciniata* (Balme & Hassell) (which extends into the overlying Anderson Formation).

All fossil groups indicate a general Tournaisian (Early Carboniferous) age. Thomas (1971) considers that the brachiopods from the upper part of the Laurel Formation (but beneath the upper shale member) are of Middle Tournaisian age whereas Hill (*fide* Thomas, 1962) considers the corals to indicate a general Dinantian (Tournaisian plus Visean) age. The ostracods indicate a general Early Carboniferous age, and further work will allow for more precision. The microflora, although varied, has been assigned to a single microflora, the 'Lycosporoid' Microflora of Balme (1964). Dating of the flora is by the contained fauna rather than by comparison with Carboniferous floras from standard successions in the Northern Hemisphere. Although some Northern Hemisphere form-genera are present in the floras, many important forms have not been recognized, including *Triquirites*, *Tripartites*, *Densosporites* and the Tholisporites-Vallatisporites group (Balme, 1964).

Depositional History

Deposition of the Laurel Formation was probably over a broad, shallow, gently sloping platform, the water depth being less than 20 metres even on the outer platform area (Fig.19). The variations in bathymetry are subdivided into four zones:

1) lagoon, with a saline restricted marine environment (Facies A(i))
2) restricted platform incorporating Facies A(iii), as well as part of a restricted platform and shoal environment Facies, A(ii)
3) shoal and intershoal region with shoal environments, in Facies A(ii), A(v), A(vi), and intershoals represented by Facies A(iv), A(v)
4) open-marine platform area, with Facies B and part of Facies A(vi) deposited in this zone.

Overall energy conditions were considerably lower than during the deposition of the Gumhole Formation. Carbonate sedimentation was dominant on the platform except in relatively deeper water on the open platform where silts and muds accumulated. Due to general shallow water conditions, restrictions in water movement caused a probable deficiency of nutrients, as well as higher salinities in the lagoon and restricted platform areas. Normal marine conditions existed around the shoal and intershoal areas, where the bathymetric variations were small but significant.

Laurel sedimentation was in quieter and steadier climatic conditions during a relative rise in sea level, producing a transgressive sequence which onlapped the regressive Yellow Drum Sandstone (Fig. 19). Throughout this transgression, small oscillations in relative sea level persisted and produced a repetition of shallow water facies in the upper part of the sequence.

STRATIGRAPHIC MAPS

In addition to information obtained from outcrop, subsurface data from 15 stratigraphic drill-holes (Appendix 1) was used in preparing stratigraphic maps. The number of control points from the Lennard Shelf and the northern edge of the Fitzroy Trough is sufficient for a regional interpretation. Control points within the trough itself are few and post-depositional tectonism and erosion of the southerly margin of the basin have left the Fairfield Group sequence incomplete. Hence an interpretation of sediment thickness and facies type in these areas is more tenuous.

The available data on each formation was used to construct isopach and entropy-ratio maps for lithostratigraphic units, as well as maps showing thickness and sediment type for specific intervals of time.

Isopach maps (Figs. 20-24)

In the northwest part of the basin, the presence of small tectonic blocks is based on aeromagnetic interpretation (WAPET, 1972b). These blocks apparently moved differentially during sedimentation. The isopach maps illustrate the elongate nature of the basin in the Late Devonian and Early Carboniferous, and emphasize the trough and northern shelf. The greatest thickness of the Fairfield Group is in the southeast, where Carboniferous sediments dominate the sequence.

Entropy-ratio maps (Figs. 25-28)

The entropy-ratio maps presented are facies maps based on three lithologies (carbonate, shale and sandstone) considered to be end members in a three-phase system. They were prepared using methods published by Pelto (1954), and Forgotson (1960).

The term entropy is used in stratigraphy as a measure of the mixing of the different kinds of rock components in a stratigraphic unit (Pelto, 1954). The entropy value of a given component is the product of its proportion in the unit and the natural logarithm of that proportion. A stratigraphic unit with equal parts of each component has an entropy value of 100; as the composition approaches that of a single component, the entropy value approaches zero.

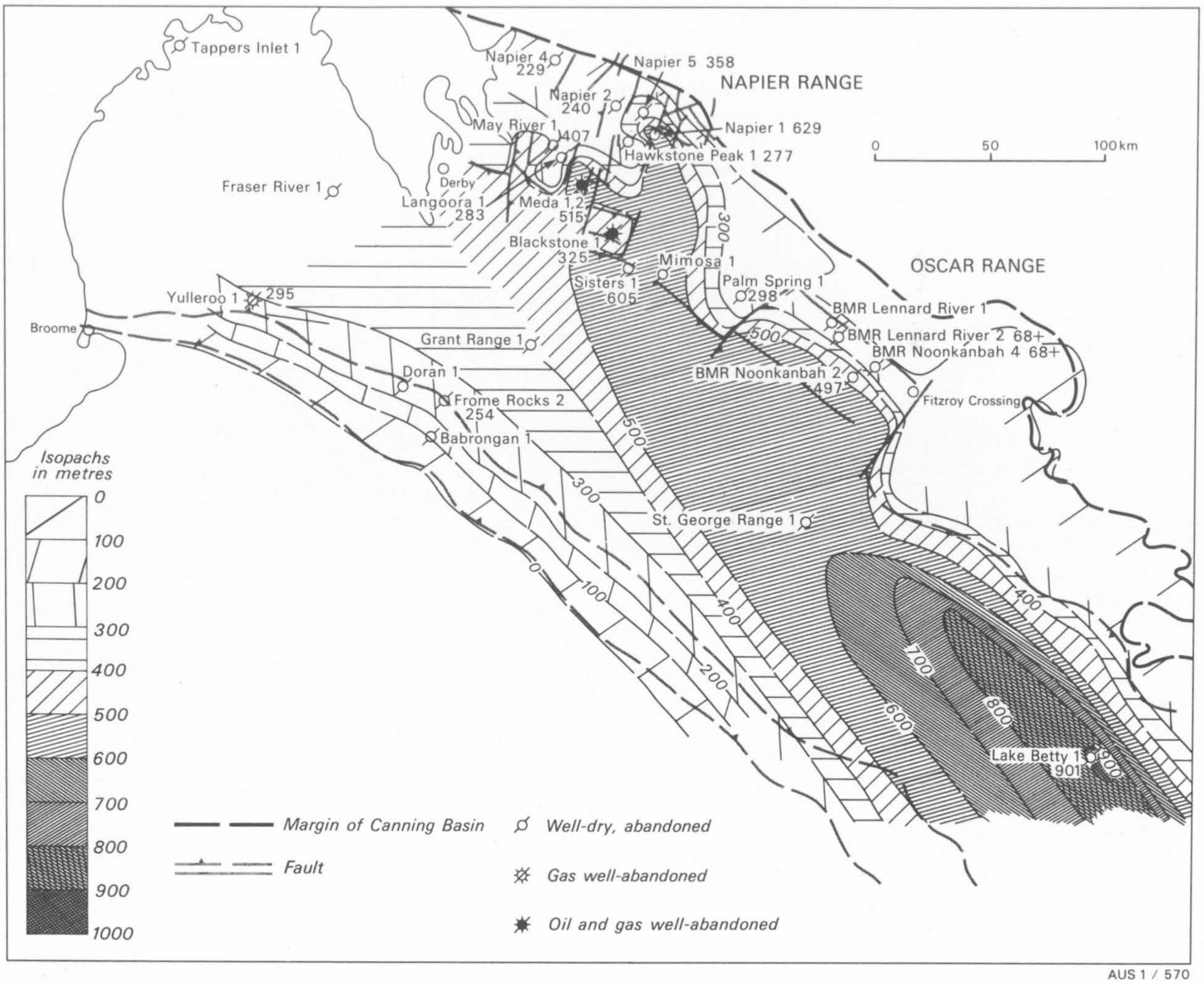

Figure 20. Isopach map: Fairfield Group.

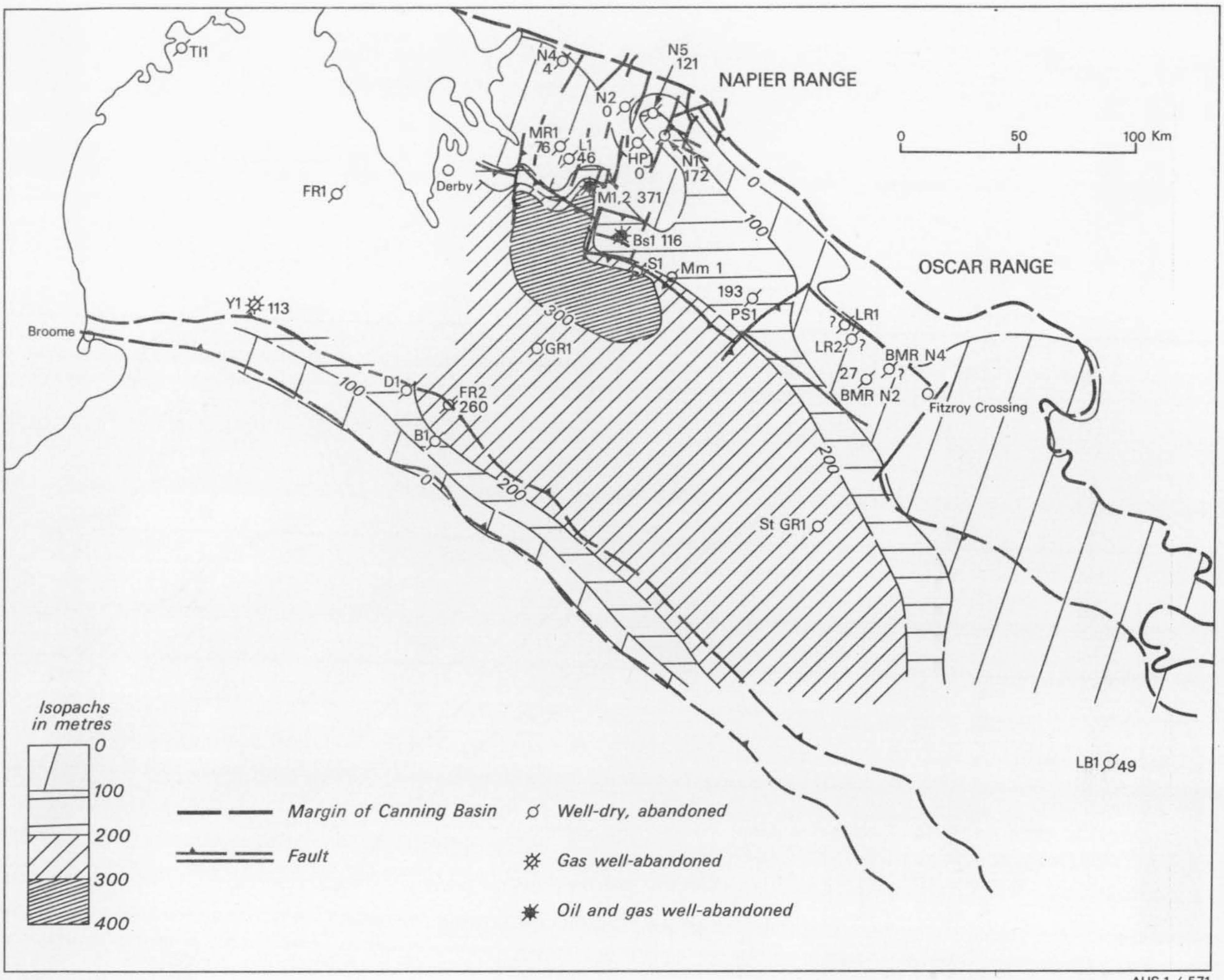

Figure 21. Isopach map: Gumhole Formation.

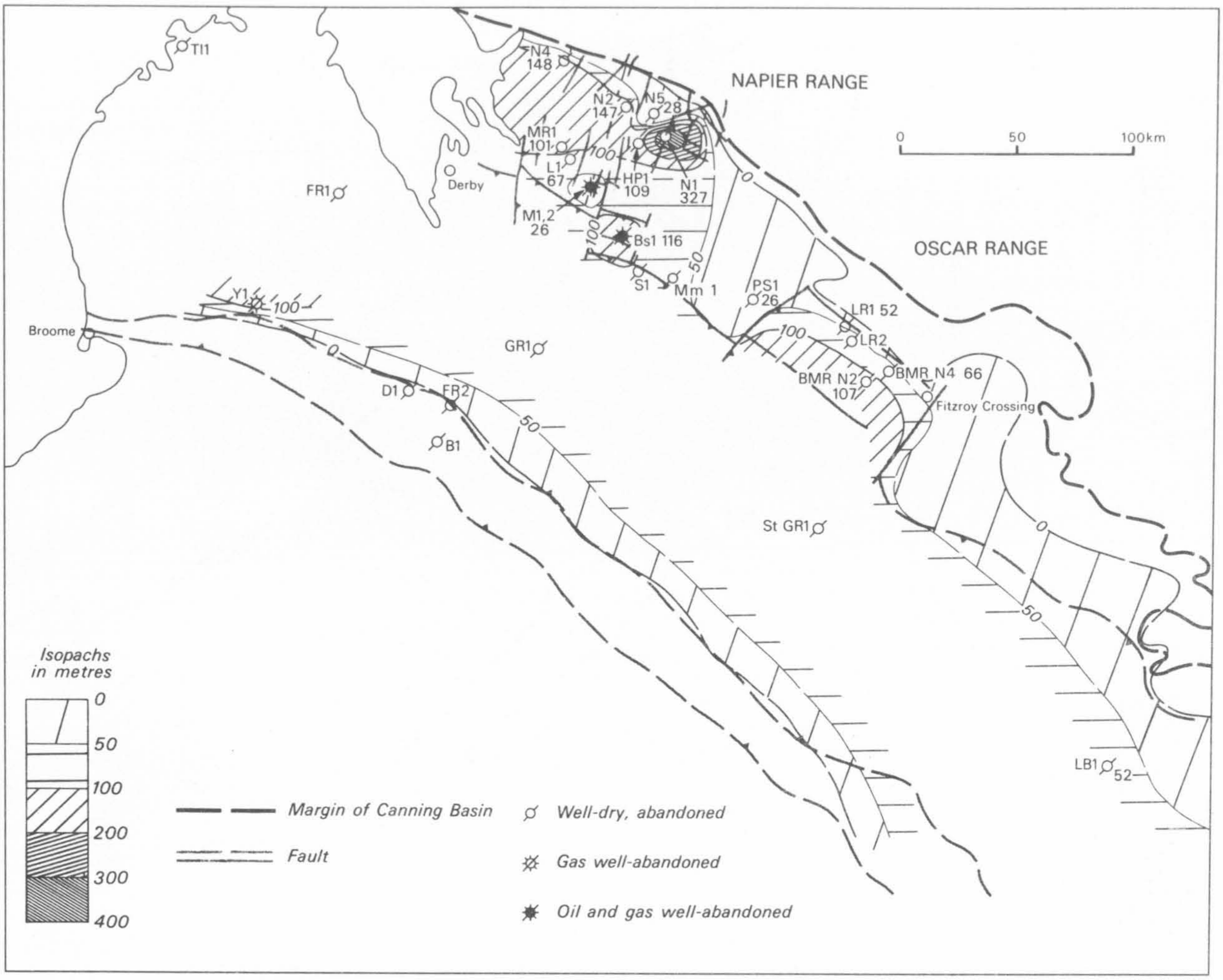

Figure 22. Isopach map: Yellow Drum Sandstone.

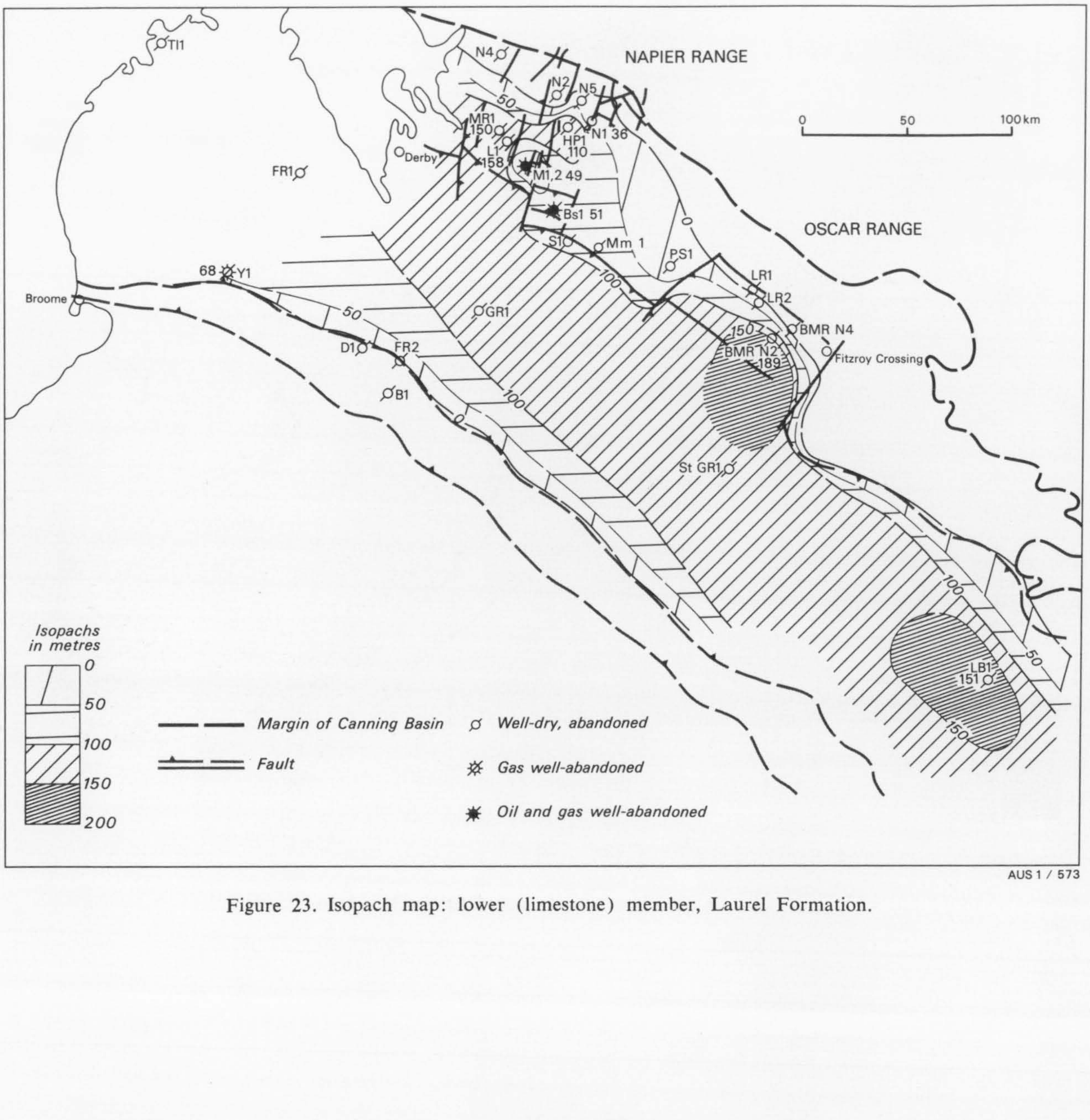

Figure 23. Isopach map: lower (limestone) member, Laurel Formation.

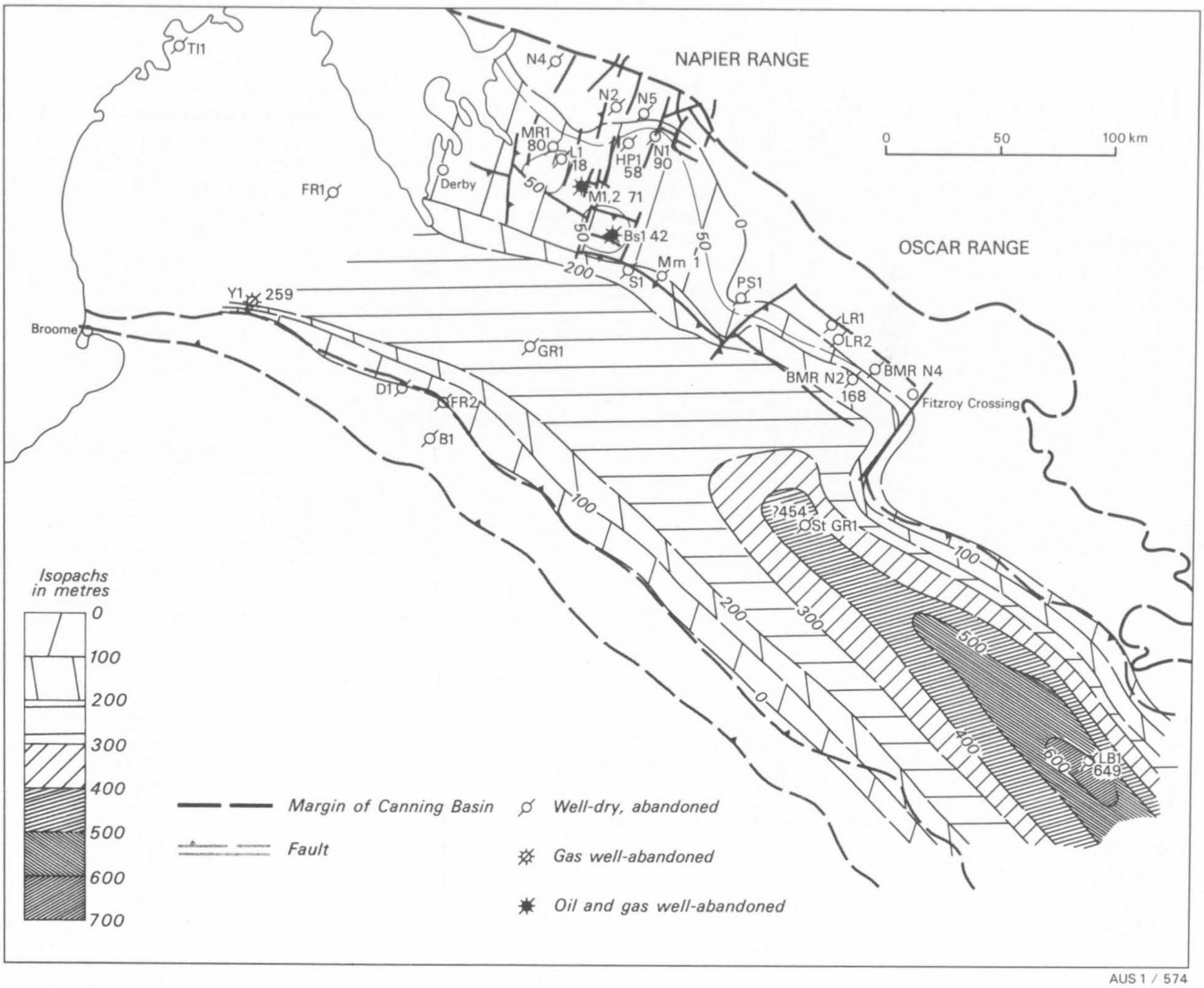

Figure 24. Isopach map: upper (shale) member, Laurel Formation.

The maps show that for each unit within the Fairfield Group the clastic component (shale plus sandstone) is more abundant toward the northerly margin.

Furthermore the entropy-ratio maps show the variations of abundance of each sediment type throughout the Canning Basin during deposition of the Fairfield Group. Within the Gumhole Formation limestone is dominant at the western end of the northerly margin, and extends as a tongue southward to the junction of the shelf and trough.

The Yellow Drum Sandstone sequences contain greater amounts of clastics; the area of carbonate dominance is small and is confined to the western part of the northerly shelf. The entropy-ratio map for the lower (limestone) member of the Laurel Formation shows that carbonate sedimentation was over the whole basin, apart from the margins where there was a dominating influx of siliciclastic material. However the upper part of the Laurel sequence represents a change in facies with a greatly increased siliciclastic content and a consequent decrease in carbonate content with, apparently, no areas of largely carbonate deposition.

TIME-INTERVAL MAPS (FIGS. 31-36)

In order to understand the changes in thickness and facies with respect to time, maps were produced for biostratigraphic time intervals based on the European standard zones. Fossils are known from the Fairfield Group in a majority of the wells drilled, although the biostratigraphy is somewhat crude and the recovery of fossils is random. To deduce possible thicknesses of rock within any standard zone, cross-sections through the basin were constructed, known ages were added and then time lines projected through the sequences in each well. Maps were then produced, showing isopachs and rock types for each time interval.

The intervals used within the Late Devonian (late Famennian) are, from oldest to youngest, doV, doV-VI, doVI (of the German Standard scale), and tnIa (of the Belgian Standard Scale); and within the Early Carboniferous (early Tournaisian), tnIb, tnIIa and tnIIb (of the Belgian Standard Scale).

These maps show the general shallowing of the basin, with a related spread of carbonate sedimentation towards the basin centre during the latest Famennian, together with the greater development of siliciclastics on the northerly margin during the latest Devonian. Subsequently, in the Early Carboniferous, greater subsidence occurred and the area of carbonate deposition decreased and was concentrated near the northerly margin.

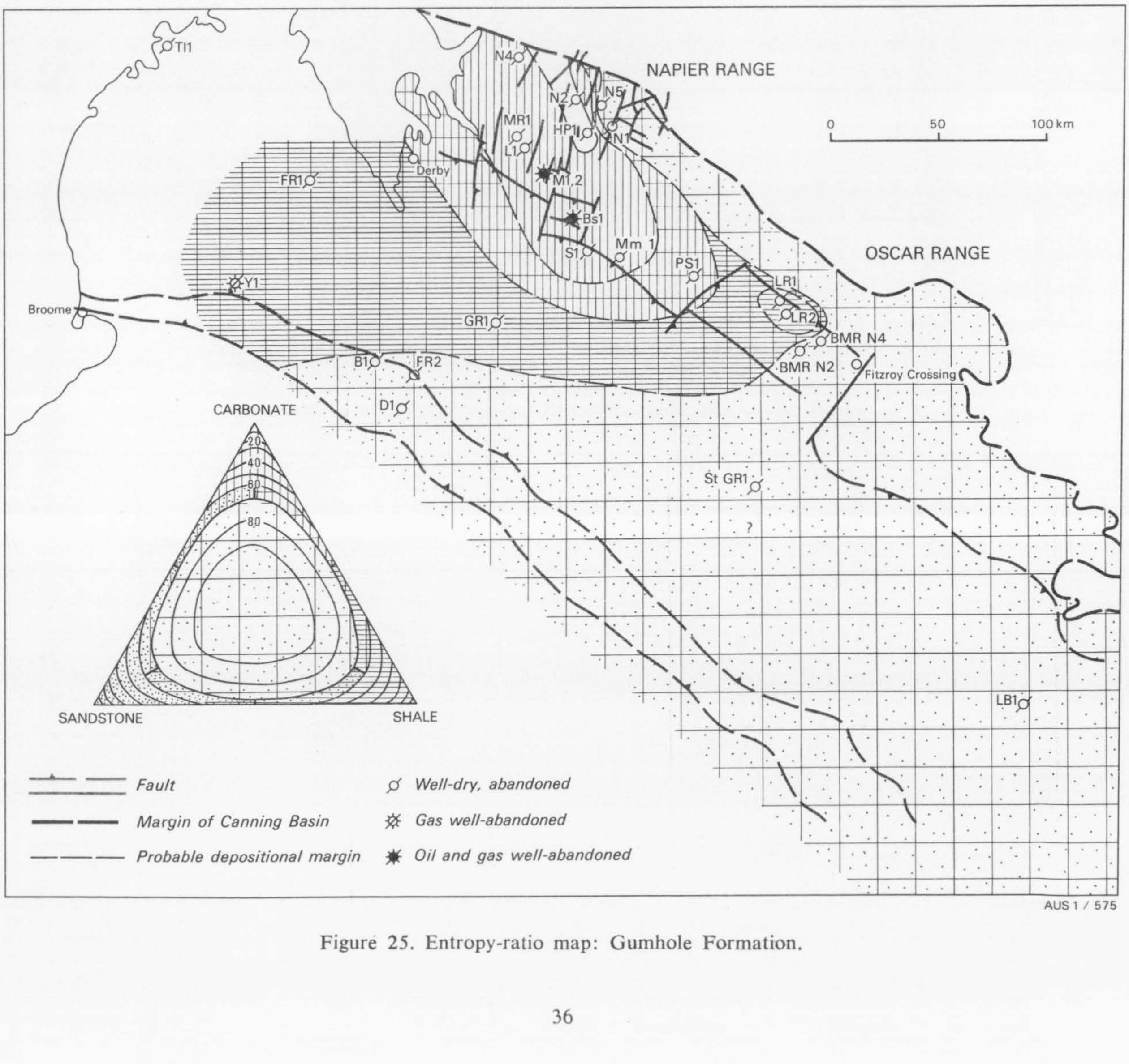

Figure 25. Entropy-ratio map: Gumhole Formation.

PALAEOGEOGRAPHY

In attempting to reconstruct the geography of the Canning Basin area during the latest Devonian and earliest Carboniferous we are concerned with the distribution of land and sea, the geomorphology of the land and depth of the sea, current directions, and distribution of bottom sediments. Within the present studies we can use evidence provided by knowledge of rock types (their distribution and relationships), petrology, geochemistry, and fossils. Information on sedimentary structures in the Fairfield Group is scant and determination of transport direction is virtually impossible. However the available information on sedimentary structures has been used in determining the genesis of facies and provides some input into the palaeogeographic reconstruction.

Pre-Fairfield Group geography

Generally the coastline on the southern edge of the Kimberley Block (on the northerly margin of the Canning Basin) was static during the Devonian and Carboniferous. Immediately prior to the commencement of deposition of the Fairfield Group the northerly margin approximated the present outcrop of the Late Devonian (Frasnian and early Famennian) reef complex (*sensu* Playford & Lowry, 1966). An exception was in the area west of Station Creek (Fig. 1), where the lack of late Famennian sediments in Napier No. 2 Well suggests that this area was emergent. We recognise this as a palaeogeographic feature, the Napier Peninsula (Fig. 31). The southerly coastline is more difficult to determine because of contemporaneous and subsequent tectonic activity, and the lack of outcrop. We have assumed that it trends southeast-northwest and approximates the southern edge of the Jurgurra Terrace (Fig. 2). An island was probably present in the vicinity of Langoora No. 1 Well (Fig. 37). The distribution of sediments (Fig. 37) shows the preponderance of marine siltstone and limestone in the basin, together with the extensive development of algal-flat carbonates in the eastern part of the northerly margin and offshore in the general area of the Napier Peninsula and associated islands. The presence of large areas of algal-flat carbonate suggests relatively shallow water depths over the northerly half of the basin, with water depth increasing toward the central part of the basin and sedimentation taking place below wave base.

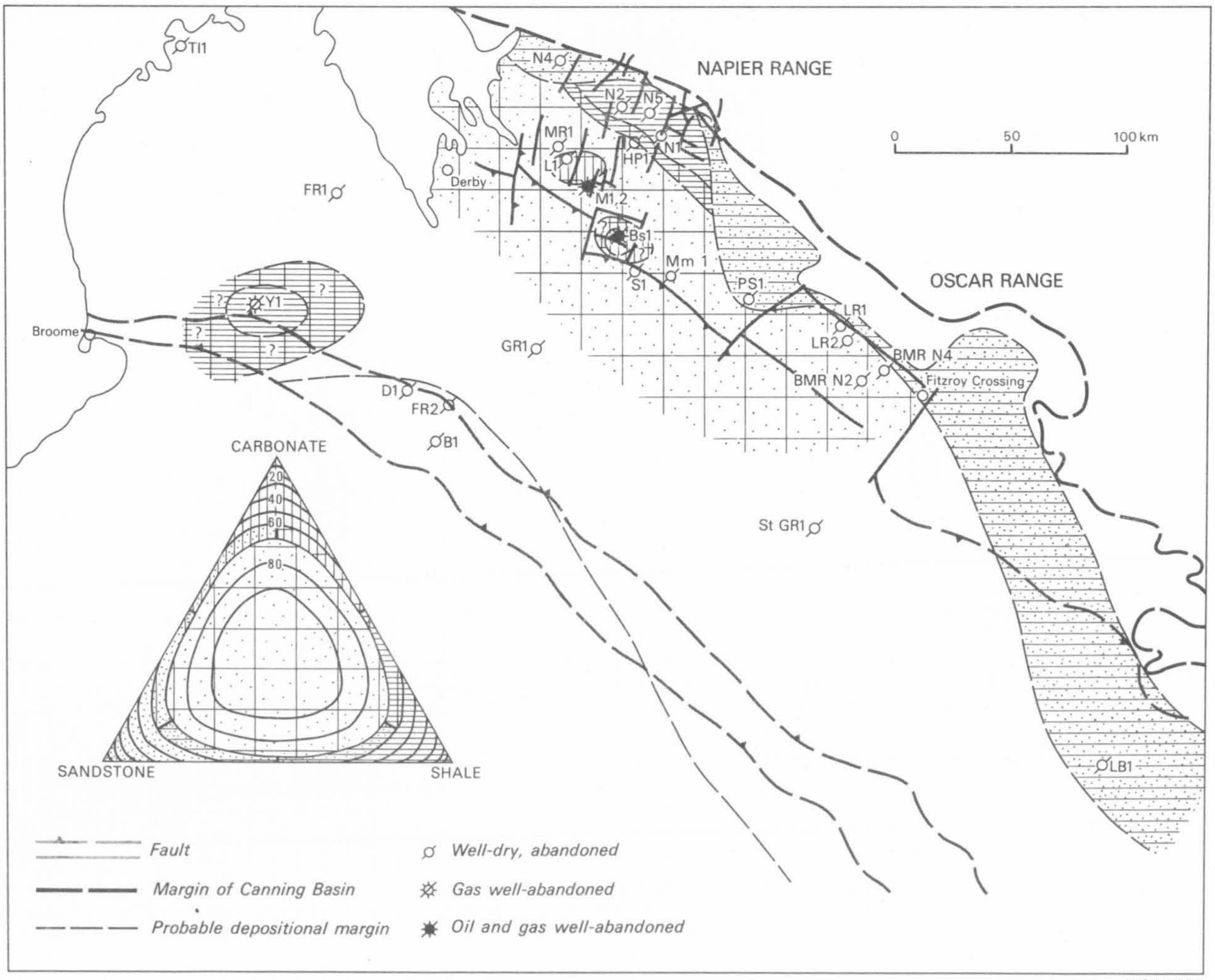

Figure 26. Entropy-ratio map: Yellow Drum Sandstone.

The presence of algal-flat carbonates and the apparent lack of coarse siliciclastic material at this time suggests that runoff was minimal: implying that the rainfall was low, the catchment area was small, or that the hinterland was low lying; or a combination of all these factors. There is no unequivocal evidence to support any one of these factors; however erosion of the hinterland had continued since at least Ordovician times and there is no evidence of extensive uplift during the latest Devonian and Carboniferous, suggesting that the hinterland may have been relatively low. Evidence bearing on the climate at the inception of Fairfield Group sedimentation is scant. Meda No. 1 Well intersected rocks interpreted as reef carbonates underlying the Fairfield Group and this suggests relatively warm conditions. Determinations of palaeolatitude (Irving, 1964) and pole position (McElhenny, 1971) indicate that the Canning Basin area was less than 10° south of the equator and therefore that conditions may have been warm to hot.

LATE FAMENNIAN TIME (doV, doV1)

The latest Famennian was marked by drowning of Langoora island, and the general emergence (Figs. 32-33) of the palaeogeographic features, the Napier and Oscar Peninsulas. During this time platform carbonates extended over the Langoora island and a regressive phase, with the incoming of sandstone in place of platform carbonates, is seen in Napier Nos. 1, 4 and 5, Hawkstone Peak No. 1 and May River No. 1. The algal-flat carbonates in the vicinity of Blackstone No. 1 are succeeded by open marine platform carbonates, suggesting that the positive area in the vicinity of Blackstone No. 1 subsided.

The geomorphology of the land surface is still unknown, but the increase in siliciclastic sedimentation, especially in the area of the Napier Peninsula and in the Red Bluffs area in the eastern part of the northerly margin, implies either increased run-off, rejuvenation, or the development of longshore drift: however the restriction of the siliciclastic facies to two areas suggests that the influx was due to localized river transport rather than longshore drift. On the other hand the non-preservation of rocks formed in a coastal environment in the Oscar Range area could present a false pattern of distribution of clastic rocks.

Spore studies (Balme & Hassell, 1962) have shown that there was probably a strongly differentiated flora of ferns and fern-like plants (pteridophytes) including lycopods (pieces of *Leptophloeum australe* (McCoy) are found in the Gumhole Formation), and horse-tails living in the coastal

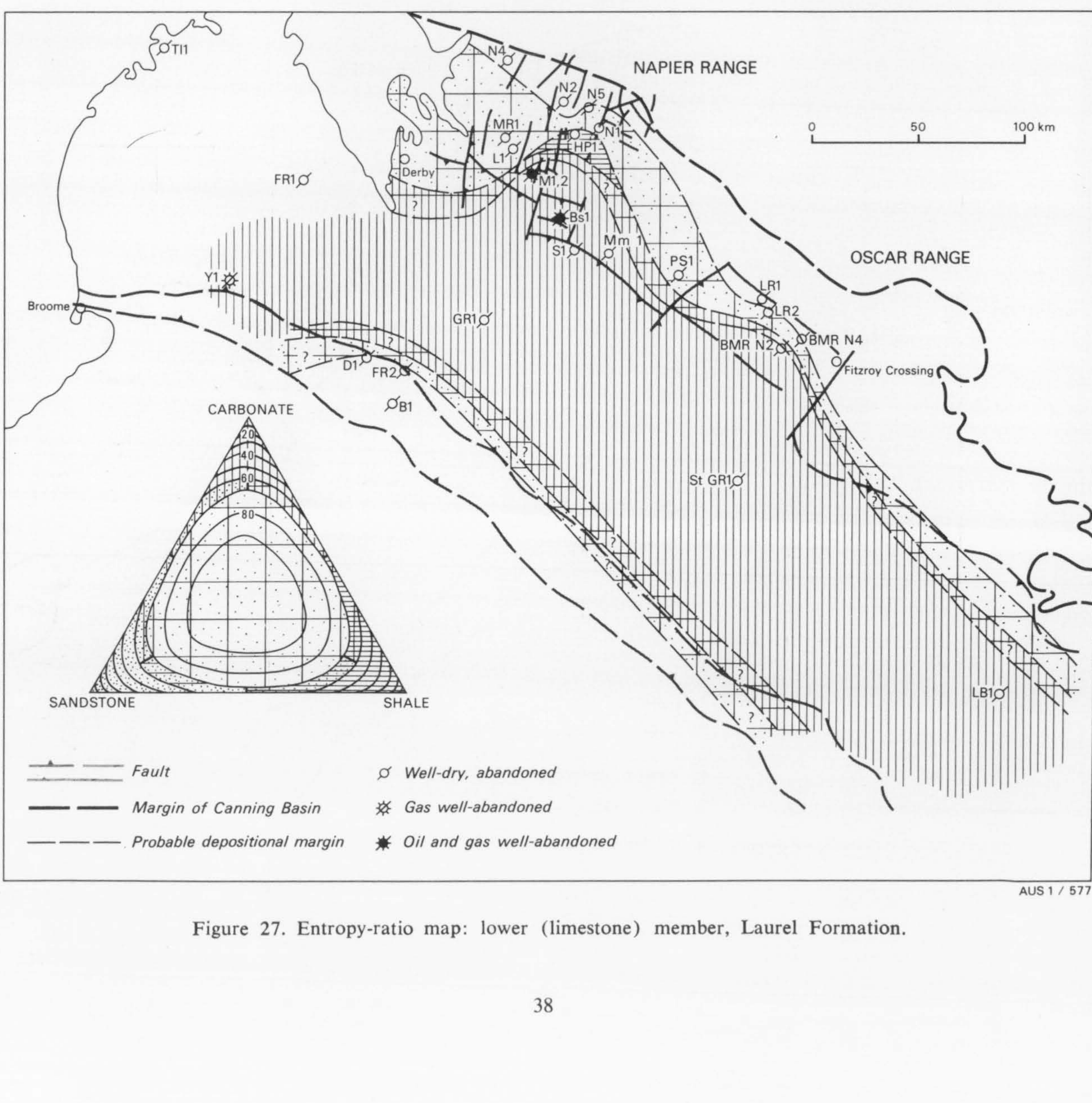

Figure 27. Entropy-ratio map: lower (limestone) member, Laurel Formation.

areas. The distribution of rock types shows not only an influx of siliciclastic material in the coastal area but also a replacement of a dominantly shale facies by a platform carbonate facies in the central part of the basin (Fig. 33) — although mud was still being deposited in the southeastern-central part of the basin. Subsidence during this period was extensive in the Fitzroy Trough and around the eastern and western margins of the Napier Peninsula and "Blackstone high" (Fig. 32). As regards the depth of water during this period, replacement of the shale facies by the platform carbonate facies supports shallowing of the basin. Within the platform carbonate sequence in the type section of the Gumhole Formation there are abundant single corals which show regrowth at 90° to the previous growth axis, demonstrating that the living animal was overturned, possibly during storms, with subsequent upward growth from the reclining calyx. Several specimens show multiple alterations of growth direction, implying that overturning was not unusual.

Petrological studies demonstrate that deposition of the carbonate facies, the Gumhole Formation in part, was in a shallow marine environment on a broad subtidal platform during a regressive phase.The fauna within the limestone indicates open-marine conditions with abundant brachiopods and ostracods; corals, spores, conodonts, and the bryozoans are abundant in some beds. The ostracods are benthonic forms and are interpreted as being shallow, warm-water forms (Jones, pers. comm); the conodonts belong to Biofacies II (Druce, 1973), characterized by the presence of pelekysgnathids, simple polygnathids, and spathognathodids which Druce (p. 211) considers to have lived in water depths of less than 50 m; the absence of Biofacies III which occupied the water mass below Biofacies II suggests that water depth may not have been greater than 50 m over the Lennard Shelf area.

The evidence for the type of climate is circumstantial; this part of Australia remained close to the equator (Irving, 1964), and the presumption of warm conditions is supported by the extensive deposition of limestone, the abundant brachiopods and common presence of corals (albeit solitary), and the pteridophyte flora. The latter also indicates that the climate was humid. The faunal evidence and the more tenuous evidence provided by rock types is supported by geochemical evidence. The Mn values in the limestones of the Gumhole Formation are similar to values which Russian workers have determined as occurring in carbonates formed in a coastal marine environment in a humid climate (Druce & Radke, 1977).

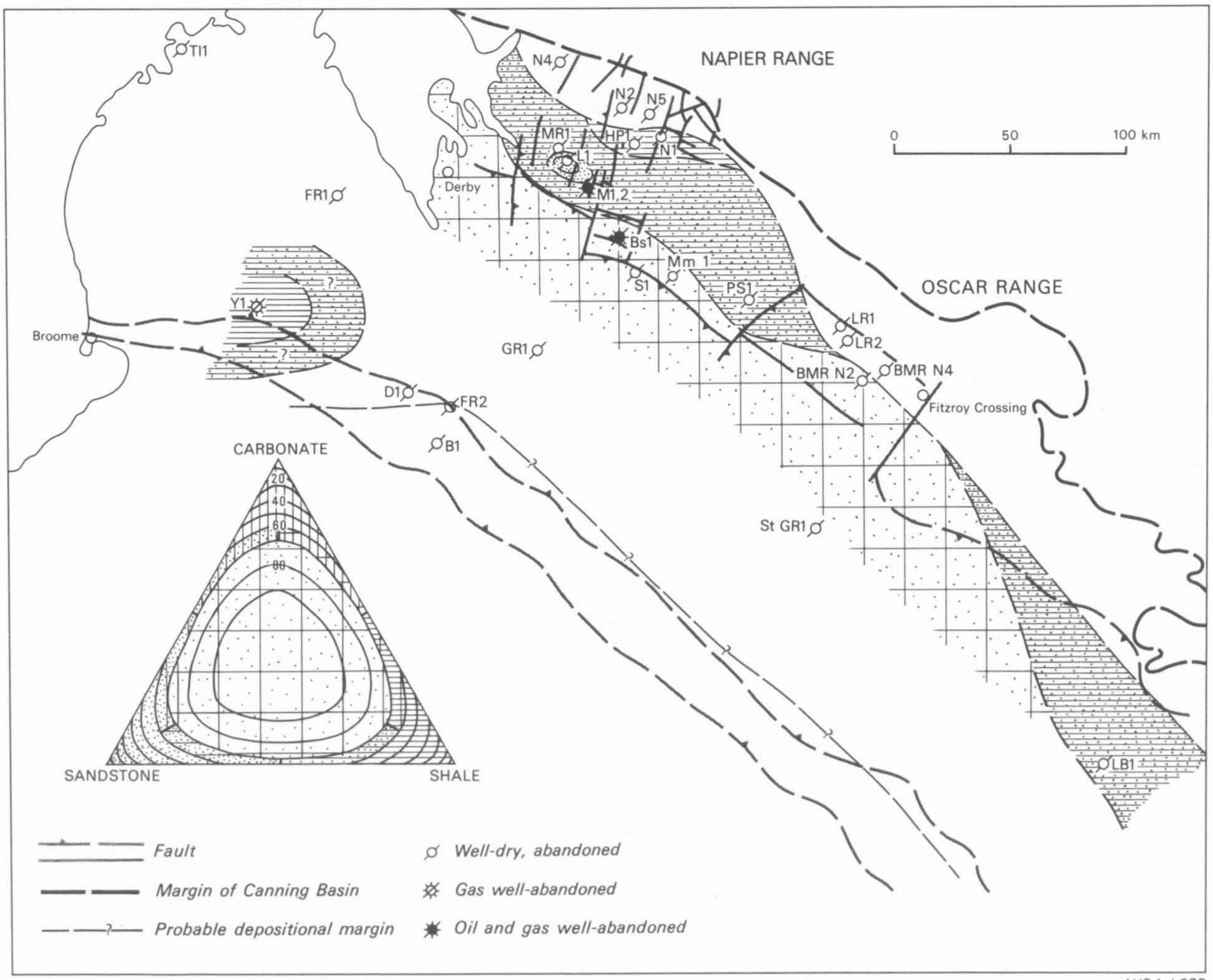

Figure 28. Entropy-ratio map: upper (shale) member, Laurel Formation.

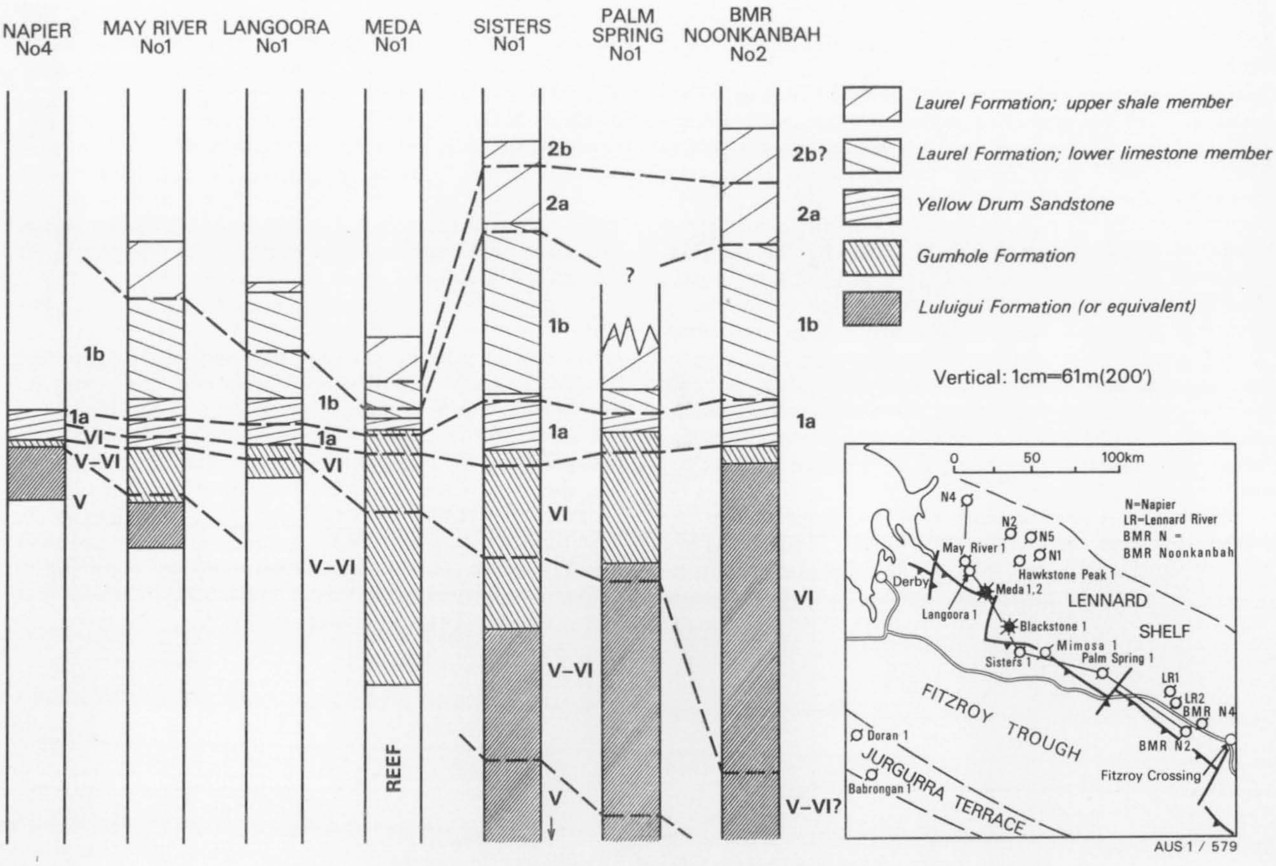

Figure 29. Columnar sections and ages, Fairfield Group, Lennard Shelf.

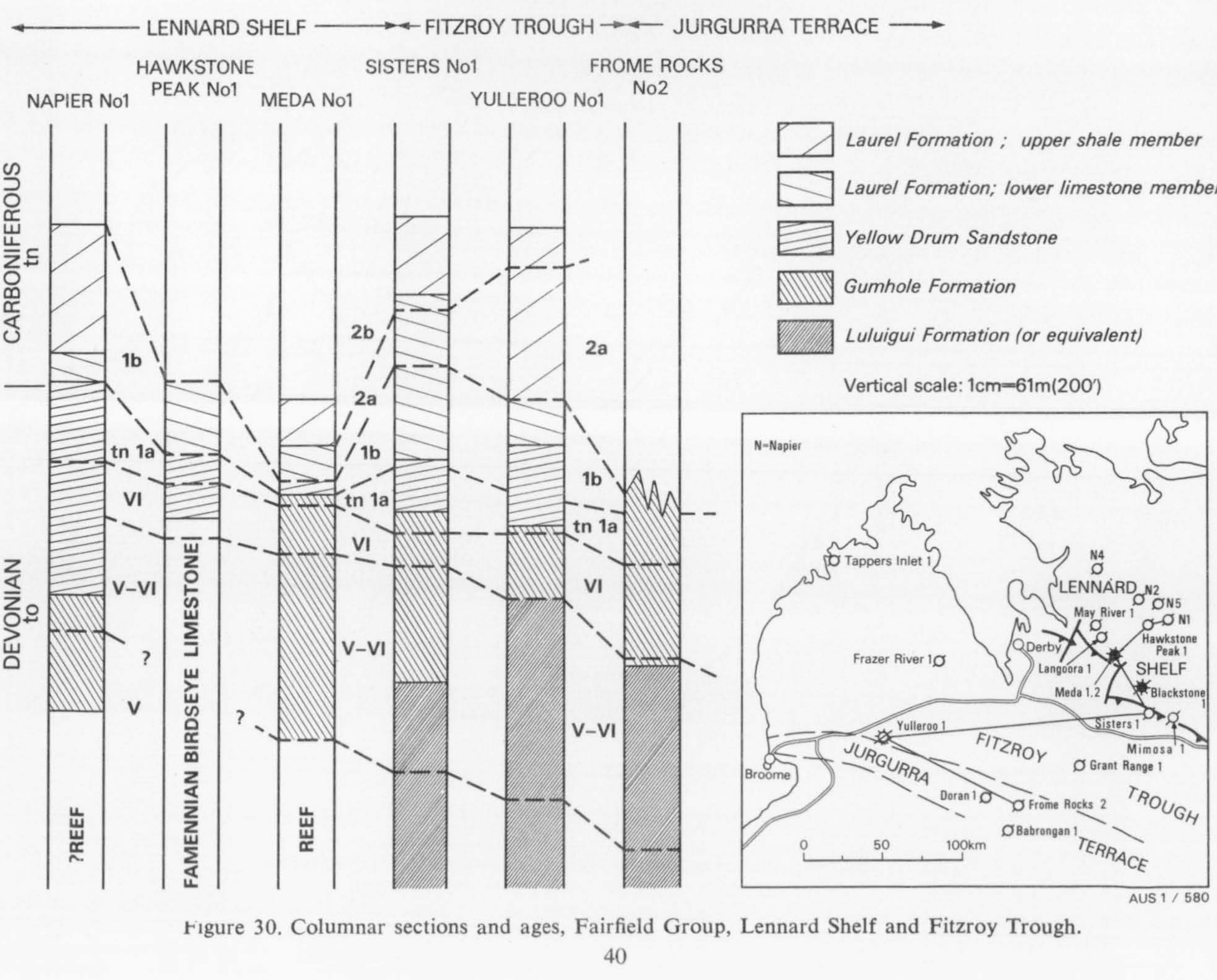

Figure 30. Columnar sections and ages, Fairfield Group, Lennard Shelf and Fitzroy Trough.

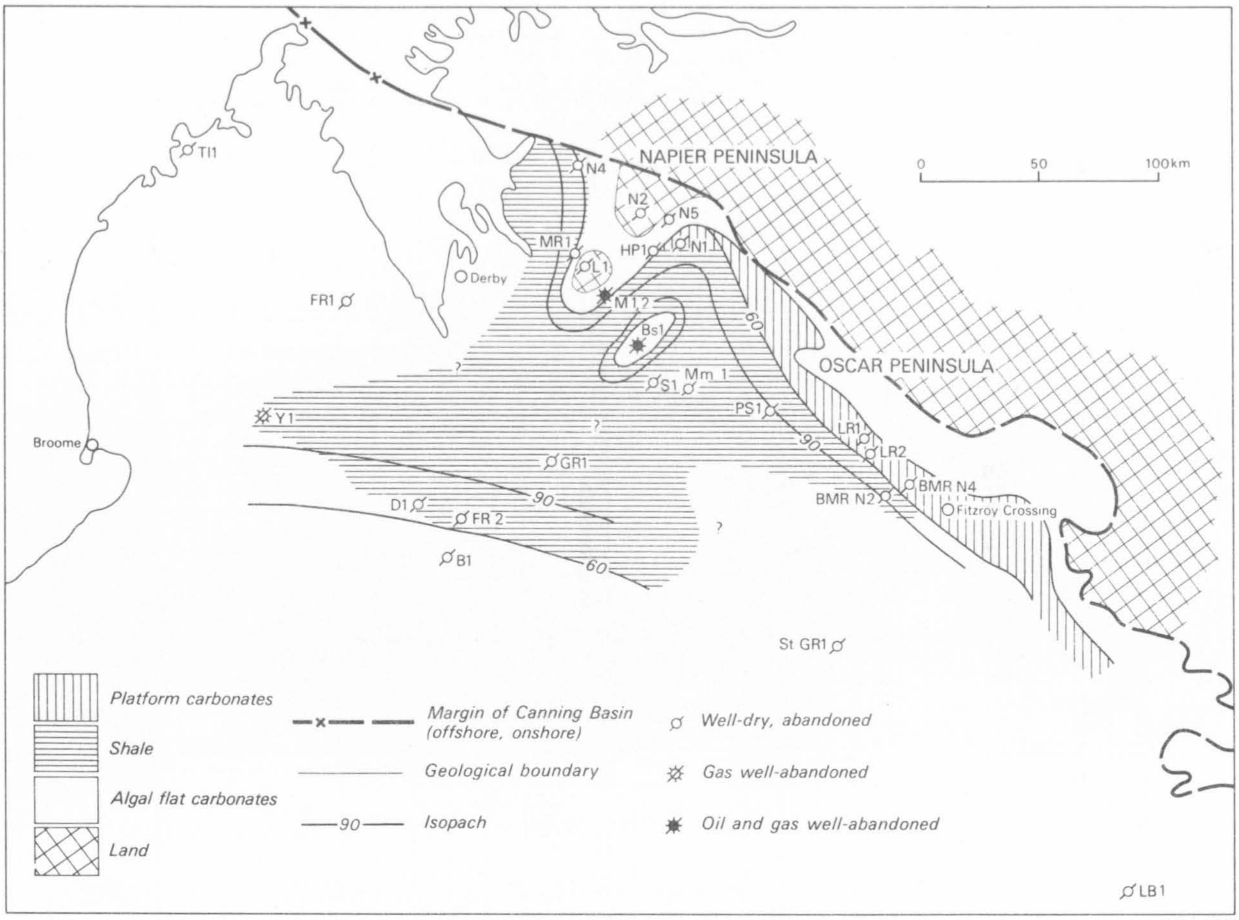

Figure 31. Lithofacies and isopachs: Late Devonian (doV).

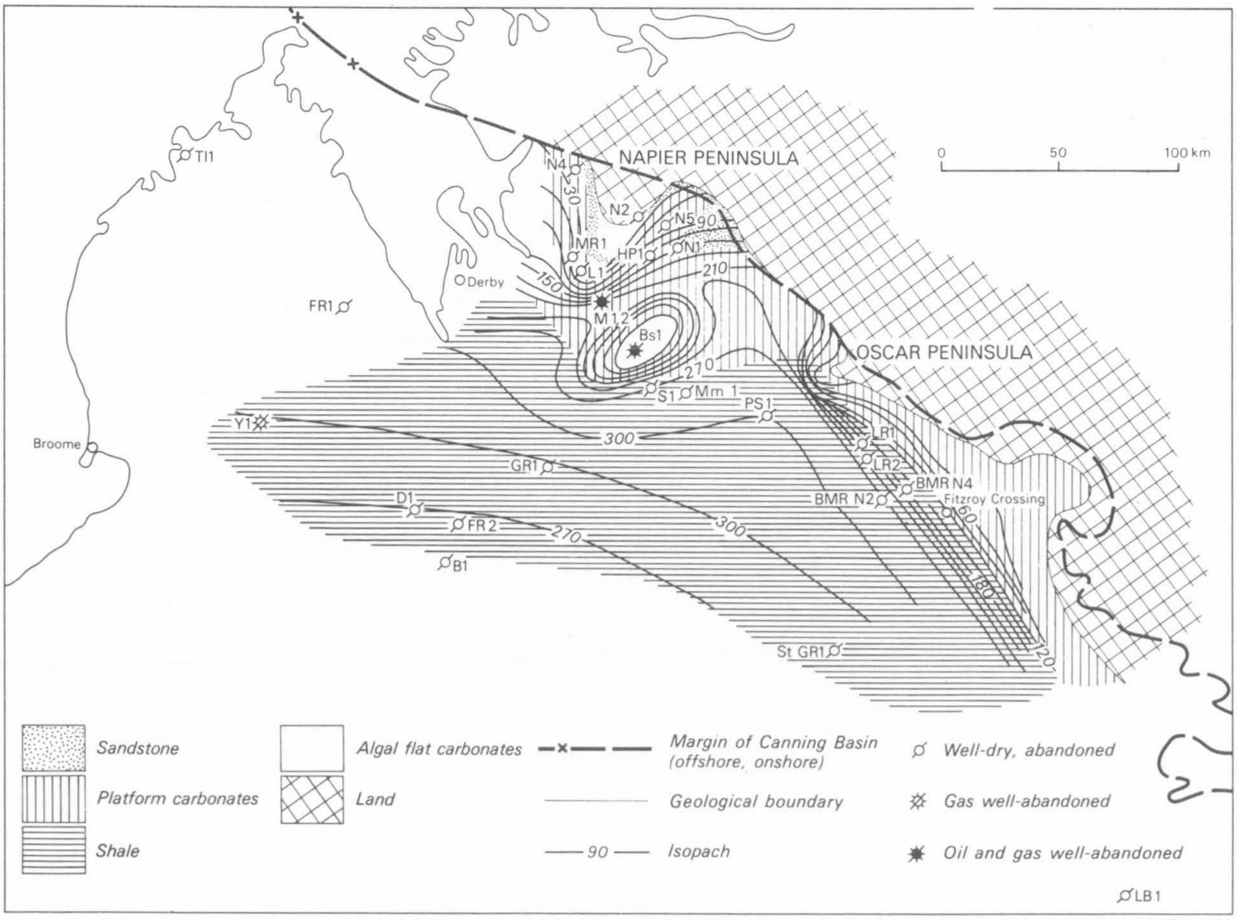

Figure 32. Lithofacies and isopachs: Late Devonian (doV-doV1).

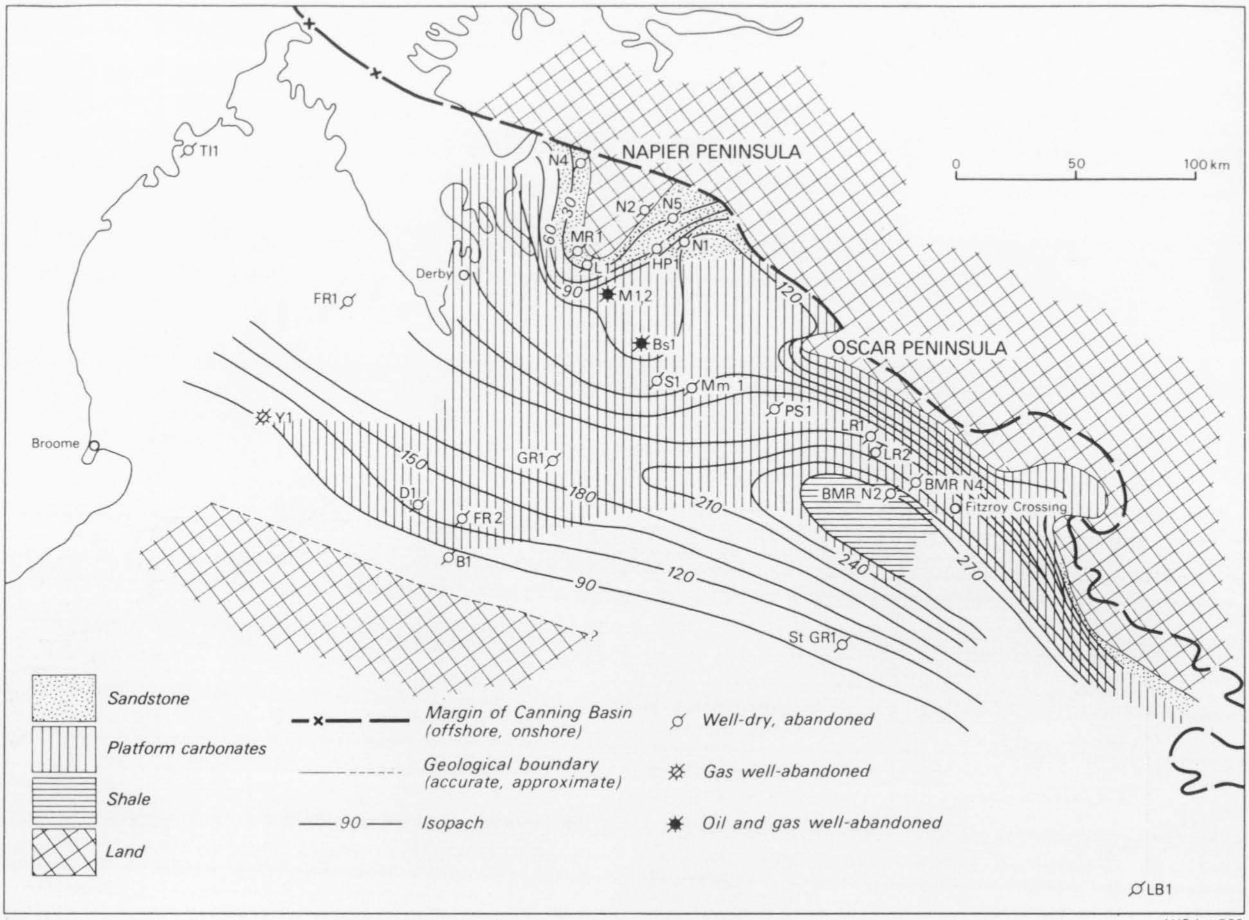

Figure 33. Lithofacies and isopachs: Late Devonian (doV1).

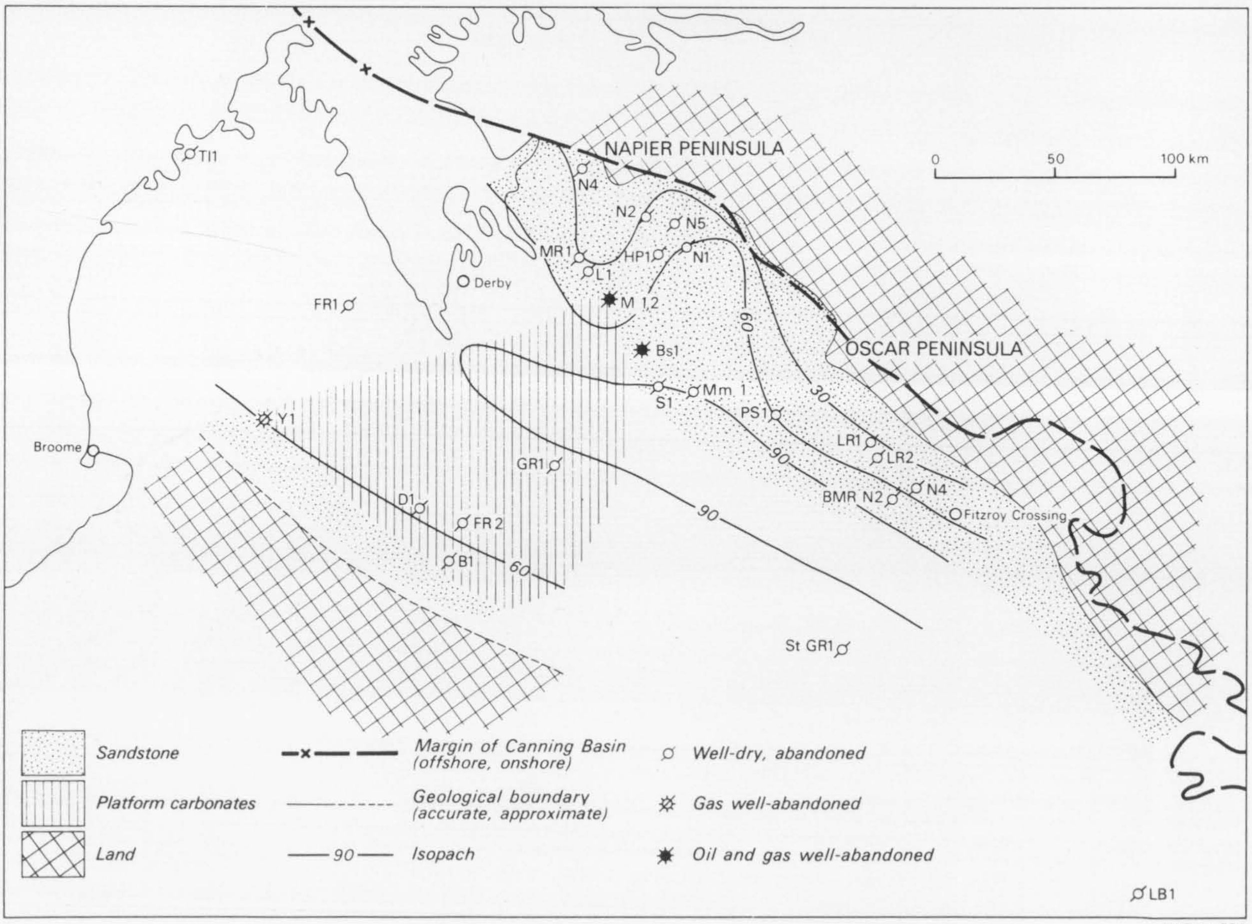

Figure 34. Lithofacies and isopachs: Late Devonian (tnIa).

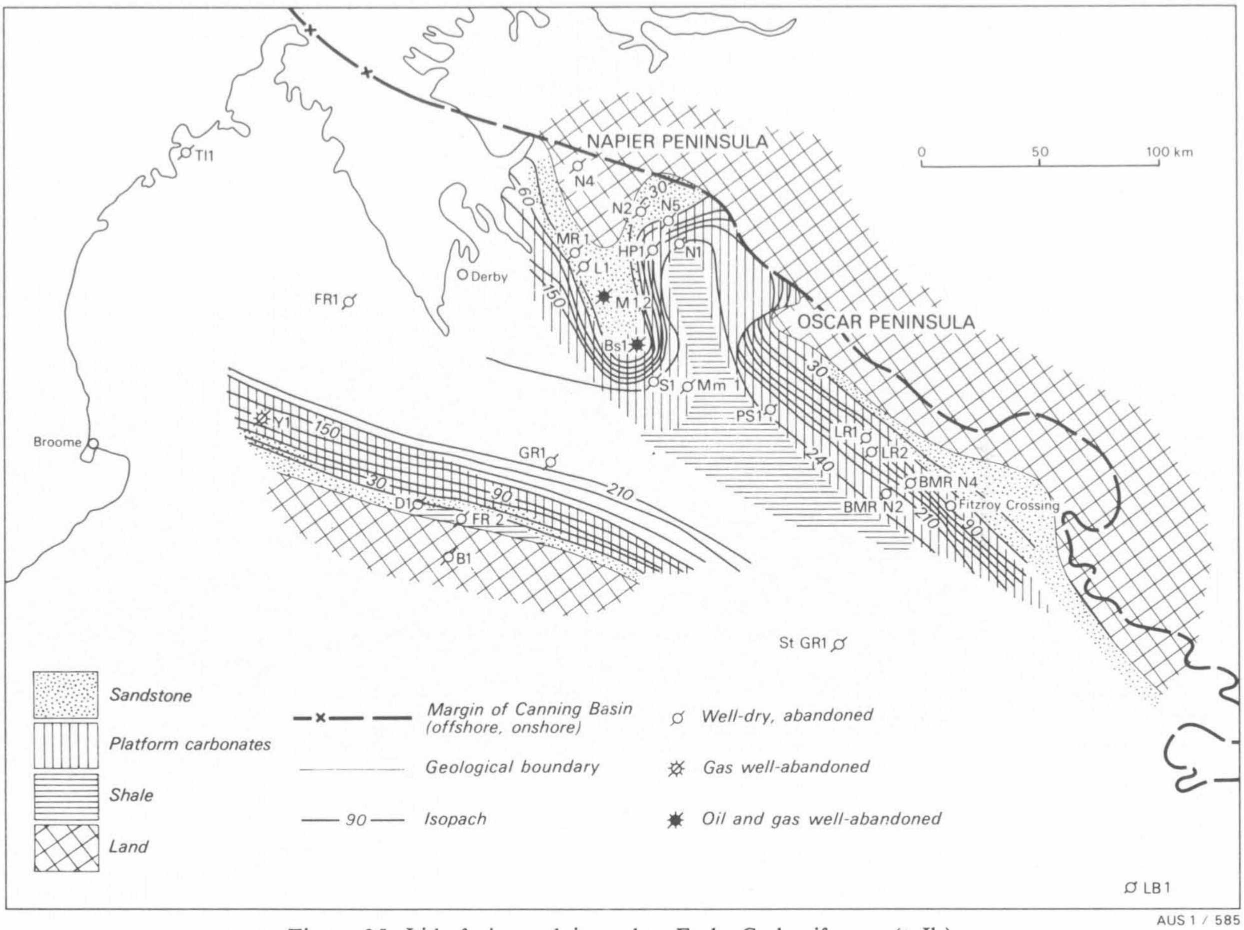

Figure 35. Lithofacies and isopachs: Early Carboniferous (tnIb).

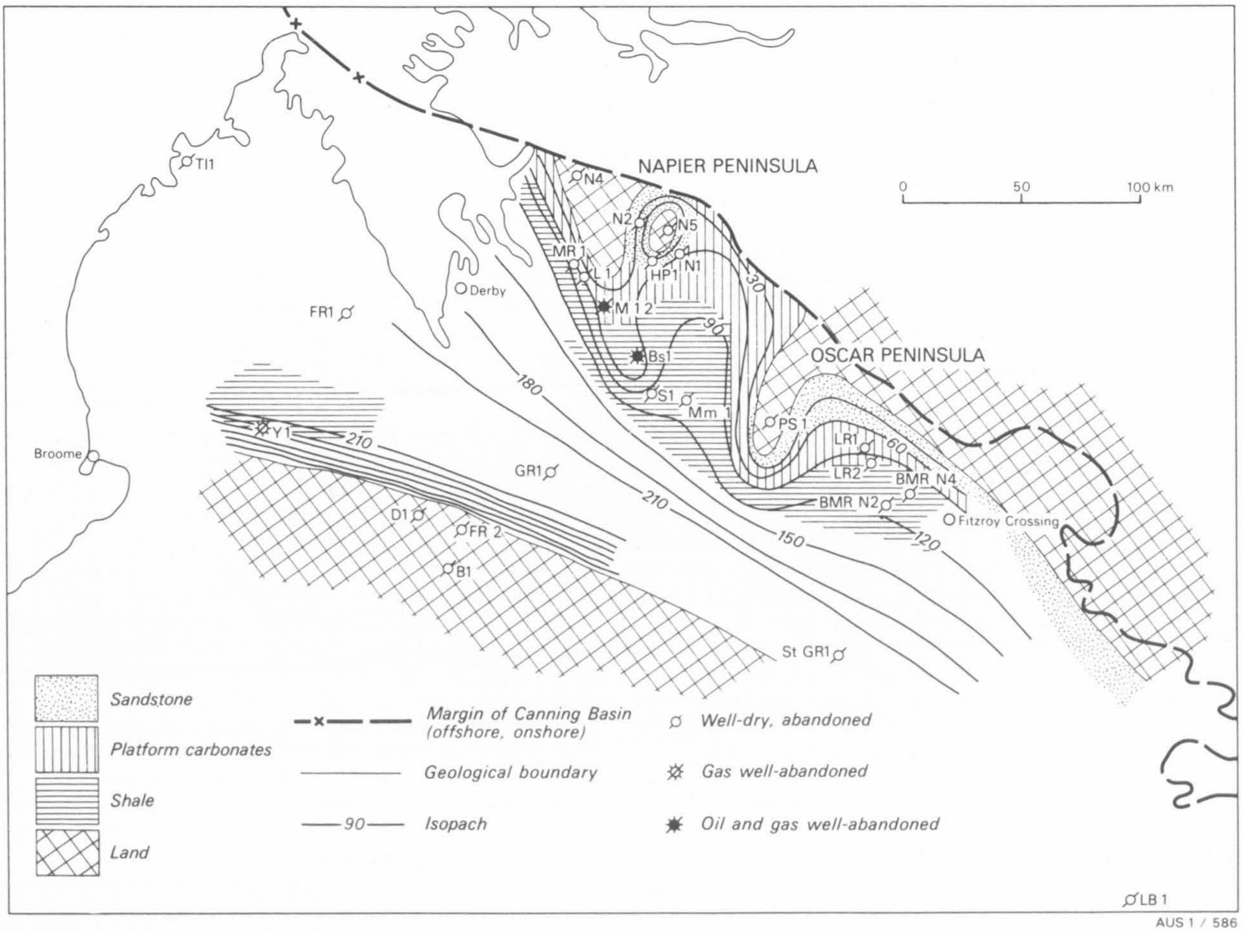

Figure 36. Lithofacies and isopachs: Early Carboniferous (tnIIa).

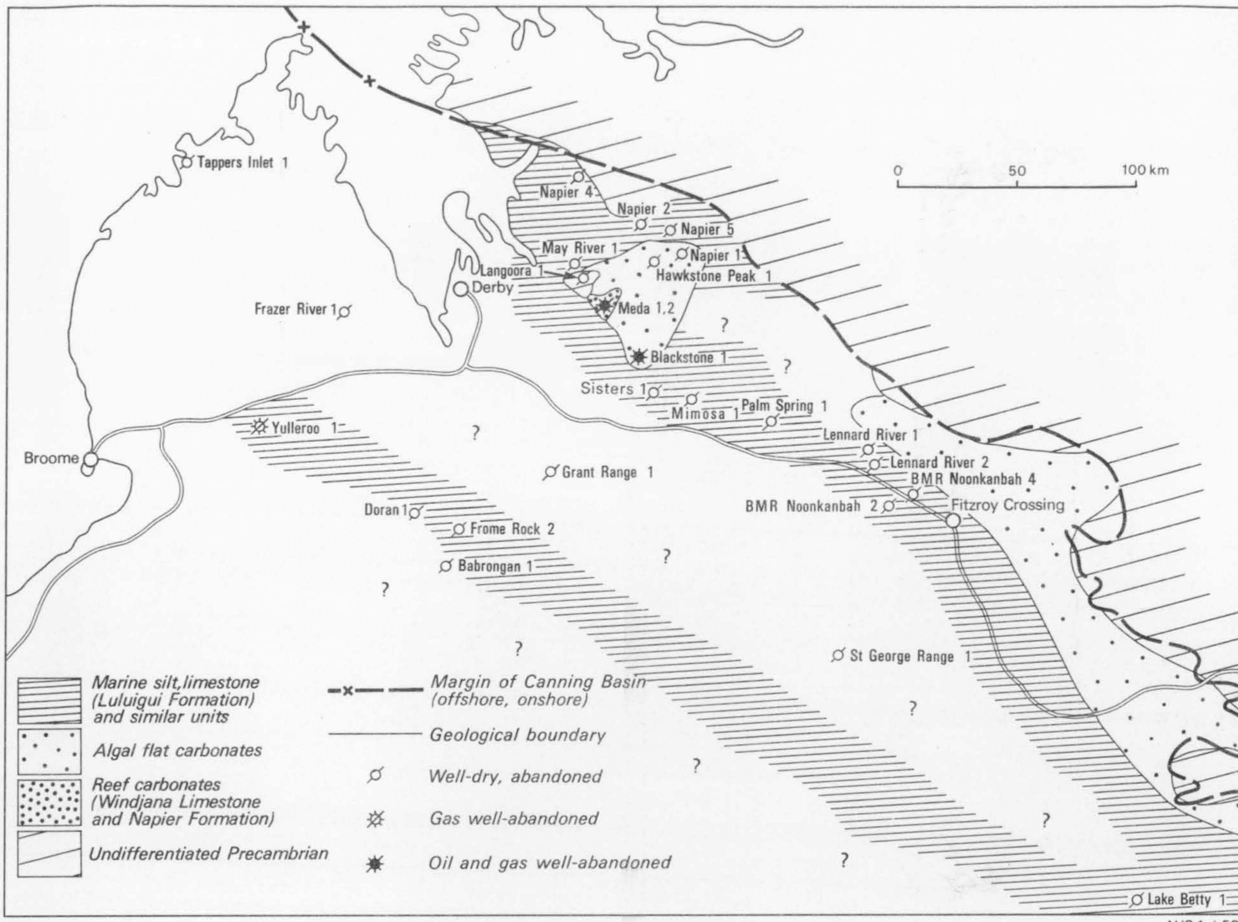

Figure 37. Geology at base of Fairfield Group.

Latest Famennian — Earliest Tournaisian time (tnIa, earliest tnIb)

This period was marked by a general shallowing of the basin and a regression accompanied by some tilting of the platform to the north, resulting not only in a movement of facies towards the basin, but also submergence of the Napier Peninsula for at least part of the time (Fig. 34). The submergence of the peninsula was the only apparent change in the configuration of the northerly coastline; the southerly coastline remains conjectural. The morphology of the land cannot be deduced with certainty, but the greatly increased availability of siliciclastic material indicates active erosion. Around the margins there was an extension of deltaic swamps and flood plains into the basin (Balme *in* Lennard Oil, 1970b). This interpretation is supported by stratigraphic evidence which suggests deposition in meandering tidal streams and emergent supratidal flats for some of the sediments.

Within the basin the rate of subsidence decreased considerably and the sandy facies extended further towards the centre of the basin with a corresponding decrease in the area of carbonate deposition and, apparently, no deposition of a dominantly shale facies (Fig. 34). The water depth during this period was reduced, and the siliciclastic facies (part of the Yellow Drum Sandstone) was deposited in intertidal and supratidal environments which extend right across the Lennard Shelf and into the area of the Fitzroy Trough.

The nature, distribution, and abundance of fossils supports this interpretation. The fauna is considerably reduced, with brachiopods, gastropods and ostracods being virtually confined to the infrequent limestone beds. The conodonts indicate Biofacies II and probably Biofacies I, which Druce (1973) has interpreted as living in water depths from 0 to about 50 m. Climate appears to have altered a little, remaining warm and humid; the increased availability of siliciclastic material implies that rainfall might have been relatively higher than during the preceding (doVI) period.

Early Tournaisian time (tnIb, tnIIa)

During this period the palaeogeographic configuration is similar to that in the Late Famennian (doV, doVI). The northerly coastline was irregular with the emergence of the Napier and Oscar Peninsulas and associated islands (Fig. 35). The southern margin remains enigmatic, but could have been farther to the north than in previous periods. This implies a general narrowing of the basin which was accompanied by subsidence — the rate of which increased rapidly towards the centre. The morphology of the surrounding land mass is unknown, but the similarity of the gross depositional pattern with previous periods, particularly the late Famennian (doVI), implies that there was little major change in topography.

The depth of the sea is interpreted as being greater than in the previous period (tnIa), because of the development of the shale facies in the central part of the basin and the corresponding narrowing of the sandy and carbonate facies towards the basin margins (Fig. 36). The increased depth may be due to a change in topography of the sea floor rather than an eustatic rise in sea level. In fact, the nondeposition of sediment on the Napier and Oscar Peninsulas and the apparent movement of the margins towards the centre of the basin, suggests that sea level may have dropped. Thus we have the involved case of a suggested general drop in sea level with, instead of the usual concomitant regression of facies, a narrowing of the facies belts and a transgression of open marine sediments over shallow-water sediments in the central area and towards the margins. The distribution of sediment is similar to that in the late Famennian (tnIa), except that a tongue of shale extends northward from the centre of the basin between the Oscar and Napier Peninsulas.

The warm humid climate of the previous periods continued; the presence of colonial corals, the types of ostracods, and the spores which indicate the development of a bryophyte-pteridophyte flora, support this interpretation.

ECONOMIC GEOLOGY

HYDROCARBONS

The presence of buried reef complexes on the northern margin of the Canning Basin has made this area a prime target for oil exploration. Drilling has continued since 1922 but, as yet, no major discoveries have been made. However, several minor shows have caused the search to be maintained and both geophysical surveys and drilling programs are continuing.

Some significant shows of oil and gas have been encountered in rocks underlying the Fairfield Group, particularly in Meda Nos. 1 & 2 (Playford, 1969). Minor shows and traces have been reported from the Fairfield Group in several wells and the first oil recorded in the Canning Basin was from the Laurel Formation in Meda No. 1 (WAPET, 1962).

Blackstone No. 1

An oil and gas show was encountered in the interval 1530-1543 m at the top of the lower limestone member of the Laurel Formation immediately below the upper shale-siltstone member.

May River No. 1

No oil or gas shows were noted, but hydrocarbon staining occurred at 1194 m, within the upper shale-siltstone member of the Laurel Formation.

Meda No. 1

This well encountered more hydrocarbons than any other well in the Canning Basin, and three shows occurred in the Fairfield Group. Two oil shows, one in each member, occurred in the Laurel Formation and a gas show was recorded from the Yellow Drum Sandstone.

The interval 1558-1565 m within the upper shale-siltstone member of the Laurel Formation yielded several gallons of crude oil from a sandstone bed between 1563 and 1565 m. A similar sandstone from within the lower limestone member of the Laurel Formation in the interval 1584-1891 also gave an oil indication on the E-log.

A 12 m interval near the top of the Yellow Drum Sandstone yielded ditch samples with staining and fluorescence, and within the interval a bed containing gas (1606-1607 m) was indicated.

Frome Rocks No. 2

No significant hydrocarbon shows were reported from this well, but waxy 'dead' oil was reported from 1180-1134 m, and fluorescent cuttings were noted from 1162-1338 m in the Gumhole Formation and in underlying strata.

Yulleroo No. 1

Several gas shows occur in this well, the majority in the sequence immediately overlying the Fairfield Group. One very strong gas show occurs at the junction of the upper shale-siltstone member of the Laurel Formation and the overlying ?Anderson Formation (3409 m). This gas contained significant amounts of higher hydrocarbons.

Areas of interest

Most hydrocarbon shows have been in thin sandstone beds in the Laurel Formation. Exceptions are the gas show in Meda No. 1 from the Yellow Drum Sandstone, and in Frome Rocks No. 2, where fluorescence and 'dead' oils are reported from the Gumhole Formation.

The Yellow Drum Sandstone is the most porous and permeable unit in the sequence and areas where it is covered (either directly or indirectly) by the siltstone-shale member of the Laurel Formation could be areas of potential hydrocarbon entrapment. These areas are located on Figure 38 together with known oil and gas occurrences.

BASE METALS

No base metal occurrences have been reported from the Fairfield Group. There are several occurrences in the underlying reef complex, and one small mine, at Narlarla (Fig. 1) has yielded about 11 000 tons of lead-zinc ore (Gellatly, 1970).

A regional geochemical study of Fairfield Group sediments was conducted in order to ascertain whether they had been subjected to mineralization or had acted as conduits for mineral-rich fluids.

No mineralization was discovered, but the geochemical survey showed that there were possibly two populations of Pb and Zn (Druce & Radke, 1977). Several samples with

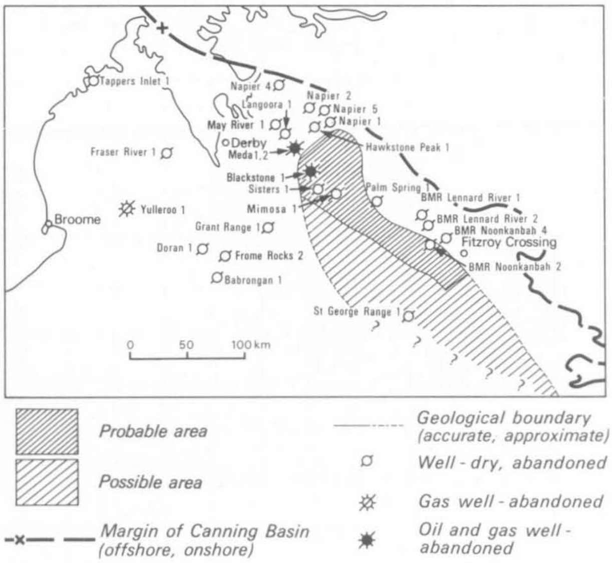

Figure 38. Area where Yellow Drum Sandstone covered by siltstones and shales of the Laurel Formation.

anomalously high values of Pb and Zn were found; these were mainly oolitic limestones with both high initial and subsequent porosities.

The evidence suggests that the Fairfield Group may have acted as a conduit for mineral-enriched fluids, but that enrichment of sediments within the Group is probably of little consequence.

CEMENT

The chemical variability of calcareous material suitable for the manufacture of Portland cement is considerable. However, certain constituents, notably Mg, are undesirable and British Standard specification BS.12:1947 for Portland cement requires that a limestone should not contain more than 2.7 percent MgO (1.6% Mg) (Johnstone, 1954). Other undesirable impurities include free silica, if too abundant and too coarse; and P_2O_5 if present in amounts greater than 10 percent. Free silica causes problems in grinding rather than affecting chemical reactions. The typical feed for Portland cement is four parts of reasonably pure limestone to one of shale (Skinner, 1969). The Fairfield Group provides the necessary raw materials for Portland cement manufacture, the limestone, siltstone, shale sequence of the Gumhole and Laurel Foundations being particularly favourable. Both have acceptable Mg and P levels and, although free silica is present, it is in the form of sand and the level is not excessive.

Consideration of the area for a possible cement industry would, however, have to wait until such time as centres of population are developed, and sources of fuel found in the region.

CONCLUSIONS

The Fairfield Group consists of a lithogenetic sequence of limestone, sandstone, siltstone, shale and dolomite formed in shallow water marine conditions. Three units, the Gumhole Formation, Yellow Drum Sandstone, and Laurel Formation can be recognised.

The Gumhole and Laurel Formations are limestone — fine siliciclastic sequences. They are separated by the Yellow Drum Sandstone, which consists of sandstones and dolostones.

The Gumhole and Laurel Formations can be differentiated in 75 percent of cases by a taxonometric analysis of their limestones, based on petrographic and geochemical properties. This result confirms the use in the field of limestone colour to separate the two units.

Limestone of the Gumhole Formation has a characteristic yellowish to rusty brown colour, and is commonly characterized by either a dominance of ooids or brachiopods, or by the presence of bryozoans. It is also characterized by higher levels of manganese, iron, lead, and zinc than limestone of the Laurel Formation; the Ca/Mg ratio is also greater in the Gumhole Formation.

In contrast, limestone of the Laurel Formation is lighter in colour, mostly white and light grey, with the diagnostic presence of pelecypods, silt, and higher levels of strontium, magnesium and calcium, and a higher ratio of strontium to calcium.

During the later Devonian and earliest Carboniferous, sedimentation patterns were influenced by the balance between organic carbonate production and terrigenous sediment influx. Deposition was in three phases, an initial transgression (Gumhole Formation), regression (Gumhole Formation and Yellow Drum Sandstone), and transgression (Yellow Drum Sandstone, Laurel Formation).

Transgressive and regressive phases are due to several interacting mechanisms, including eustatic change in sea level, subsidence, and regional and local tilting.

Deposition of the Gumhole Formation was on a broad, very shallow marine platform, under generally turbulent conditions in open marine, shoal, intershoal and restricted platform environments.

An increase in terrigenous sediment supply during a regression controlled the coeval deposition of the Yellow Drum Sandstone. Sedimentation was on partially emergent mudflat areas of higher than normal salinity, these mudflats being cut by broad shallow river channels and terminating in estuaries.

The area of deposition of this unit was increasingly restricted, while coeval sedimentation of the Laurel Formation expanded with an ensuing transgression.

The Laurel Formation was deposited on a shallow marine platform in quiet conditions in open marine, shoal, intershoal, restricted platform and lagoonal environments.

Suitable conditions for hydrocarbon entrapment probably occur in an area southwest of the Oscar Range, immediately basinward of the Lennard Shelf, in the Fitzroy Trough. The Fairfield Group contains two lead-zinc populations; it probably does not contain significant mineralization, although it may have acted as a conduit for mineralizing fluids.

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APPENDIX I

FAIRFIELD GROUP IN THE SUBSURFACE

The stratigraphic and lithological limits of formations within the Fairfield Group in the subsurface are discussed well by well; the wells are listed alphabetically from the Lennard Shelf, the Fitzroy Trough and Jurgurra Terrace (Fig. 2).

LENNARD SHELF

Blackstone No. 1

Blackstone No. 1 well is located at 17°35'14"S, 124°21'01"E, 88 km east-southeast of Derby, and about 105 km west-northwest of the type area of the Fairfield Group. The nearest wells are A.F.O. The Sisters No. 1, 17.5 km to the southeast, and Meda Nos 1 & 2, 27 km to the northwest.

The well was spudded in Triassic Erskine Sandstone, and intersected the Fairfield Group between 1486 m and 1811 m, a total thickness of 325 m.

The Gumhole Formation overlies late Famennian birdseye limestone at 1811 m; it comprises 112 m of limestone with thin shale interbeds. The limestone is light to medium brown-grey, occasionally off-white and pale brown, composed of very fine to medium, occasionally coarse, subangular to sub-rounded moderate to well sorted, detrital carbonate grains set in a clear sparry calcite cement (WAPET, 1967a). Fossils include bryozoans, crinoids, foraminifers, ostracods and algae.

The Yellow Drum Sandstone overlies the Gumhole Formation; the contact is at 1699 m. The unit consists of 116 m of dominant dolostone with minor limestone and minor shales, siltstones, and sandstones.

The dolostone is off-white to pale brown-grey with scattered small finely to coarsely crystalline clear calcite patches, and some quartz silt forming up to 20 percent of the rock. The rare laminations are formed by colour changes or grainsize variations; the laminations are generally undisturbed. Rare contortions are prbably due to bioturbation. The limestone is present in the interval 1579 m-1599 m, and is fine-grained pale greenish grey to greyish brown. Siltstone and sandstone interbeds may be present. Fossils are rare. The shale beds are dark grey and finely micaceous, and are present near the base of the sequence.

Overlying the Yellow Drum Sandstone is the Laurel Formation consisting of a 51 m lower limestone member and an upper 42 m siltstone member in the interval 1486-1579 m.

The limestone member consists of interbedded limestone, sandstone and siltstone. The limestone is bioclastic, light to medium brown and greyish brown, and slightly to very sandy. Fossils are abundant and include brachiopods, pelecypods, fish, bryozoans, crinoids, and ostracods. The sandstone is light grey, medium grey-brown, fine grained, with very little calcite cement. The siltstone occurs as stringers within the limestone and as medium to dark grey calcareous beds.

The upper siltstone member consists of dominant siltstone with minor sandstone. The siltstone member is light to medium grey, coarse-grained, sandy, micaceous and in some places calcareous. The rare sandstone is light to medium-grey and fine-grained.

Previously only the Laurel and Fairfield Formations had been recognized (Johnstone, 1968, unpubl.), the Laurel between 1486 m and 1579 m and the Fairfield Group between 1579 m and 1915 m. Within this latter interval we recognize three units, a birdseye limestone between 1811 m and 1915 m, the Gumhole Formation between 1695 m and 1811 m, and the Yellow Drum Sandstone between 1579 m and 1699 m.

There is little variation between rock types in the Gumhole Formation in the type area and in Blackstone No. 1. However the Yellow Drum Sandstone shows considerable variation, being predominantly dolostone with minor sandstone in Blackstone No. 1, whereas in the type area both dolostone and sandstone are equally represented. The laminated dolostones suggest that the environment of deposition was supratidal or lagoonal, and deposition probably took place in a restricted area which may have been periodically inundated and hence bioturbated.

The Laurel Formation in Blackstone No. 1 is closely comparable to that in the type area and is similarly composed of two members; however the thickness is greatly reduced.

Hawkstone Peak No. 1

The Hawkstone Peak No. 1 Well is situated at 17°14'45"S, 124°24'26"E, 80 km east of Derby. The nearest wells are Napier No. 1 12 km east-northeast, and Meda No. 1 29 km to the southwest; Hawkstone Peak No. 1 is 120 km to the northwest of the Fairfield type area.

The well was spudded in Permian Grant Formation and intersected the Fairfield Group in the interval 186 m-463 m before passing into Famennian birdseye limestone. The Gumhole Formation is apparently missing and the Yellow Drum Sandstone rests directly on the birdseye limestone. However cuttings from the 7 m interval 456-463 m suggest that limestone rather than dolostone may be present, and this may represent the Gumhole Formation.

The Yellow Drum Sandstone was penetrated in the interval 354 m-463 m. The 109 m section is composed of sandstone, siltstone, shale, and dolostone, with minor limestone. The lithic sandstone is fine to coarse-grained; the calcareous siltstone is mottled grey, tan and red. The shale is dominantly grey and the dolostone grey to tan (WAPET, 1966).

Fossils are rare and consist of a poorly preserved microflora, which includes spores and plant fibres, ostracods (*Paraparchites* and *Cavellina*?) and *Umbella*, a problematic genus which has been referred to both the foraminifera and algae.

The Laurel Formation consists of a limestone member and an overlying shale member. The limestone is grey-brown, bioclastic, and poorly sorted; it grades into calcareous siltstone. The shale is predominantly coloured in shades of grey, and is occasionally silty and sandy. The few macrofossils reported come from Core No. 1 (262.5 m-267 m) which is a shell bed with a siltstone matrix. Brachiopods, especially a spirifer, predominate and are similar to forms from the Laurel Formation, and also the Septimus Limestone of the Bonaparte Gulf Basin. Other fossils include crinoid stems, fish plates and fragmentary ostracods (Coleman *in* WAPET, 1962). The carbonaceous siltstone from Core No. 1 yielded a well preserved and diverse microfloral assemblage including spores and microplankton and a scolecodont (Edgell *in* WAPET, 1962).

Our interpretation differs greatly from that proposed by WAPET (1966); they recognized the Fairfield Formation between 360 and 591 m, and the Laurel Formation between 244 and 360 m. We consider that the lower part of their Fairfield Formation between 463 and 591 m represents the unnamed late Famennian birdseye limestone and the upper part between 360 and 463 m to be equivalent to the Yellow Drum Sandstone.

The upper boundary of the Yellow Drum Sandstone is taken at 354 m, thus placing 6 m of the Laurel Formation (*sensu* WAPET) within it. Apart from the lower 6 m the Laurel Formation recognized by WAPET is equivalent to the lower limestone member; the upper shale member (186 m-244 m) was originally referred to the "Glacial Member" of the Grant Formation, although the indentification was uncertain and the possibility of its being part of the Laurel Formation was not discounted.

Langoora No. 1

The Langoora No. 1 Well is located at 17°18'07"S, 124°06'48"E, 50 km east of Derby (WAPET, 1962). The nearest wells are May River No. 1, 7 km to the north-northwest and Meda No. 1 15 km to the southeast; Langoora No. 1 is 130 km northwest of the type sections of the Fairfield Group.

The well was spudded in Triassic Blina Shale and penetrated the Fairfield Group in the interval 1308-1597 m. The Gumhole Formation directly overlies Precambrian schist and is 46 m thick, the lower 15 m of which probably consists of a basal conglomerate with a limestone matrix. The upper part of the unit is composed of limestone and siltstone. The limestone is cream and grey to brown, fine to coarse sandy and silty in part, and in places is oolitic. The siltstone is light grey-green to grey, grading to fine calcareous quartzose sandstone. Few fossils were recovered and preservation was poor although sufficient to suggest a Devonian age. Spores were recovered from Core 10 (1551-1559 m) and are long-ranging forms (Fowler *in* WAPET, 1962); foraminifera from the same core suggest a correlation with the Upper Devonian of Russia (McTavish *in* WAPET, 1962).

The Yellow Drum Sandstone was intersected in the interval 1484-1551 m and consists mainly of dolostone with minor siltstone. The dolostone is off-white to tan, very fine to finely crystalline, and sugary in texture. The siltstone is dolomitic, tan to brown, and grey, calcareous in part, and commonly sandy. The only fossils reported are indeterminate moulds of ostracods from a sidewall core at 1521 m (McTavish *in* WAPET, 1962a).

The Laurel Formation was penetrated between 1308 m and 1484 m, and consists of a lower limestone member and an upper shale member. The lower member is 158 m thick and is composed of dominant limestone with minor siltstone, shale, and sandstone. The limestone is tan, brown, and grey, sandy with abundant fossil fragments, and is in part oolitic. The silty limestones grade into tan, brown, and grey siltstone which is micaceous, in places calcareous, and rarely carbonaceous. The shale is light green, the sandstone off-white to grey and very fine to fine-grained. The upper member is 18 m thick and is dominantly siltstone with minor shale, and limestone. The siltstone is light to medium grey to tan in colour; it is calcareous, micaceous, fossiliferous and sandy in part. The limestone is tan to grey-brown, of fine to medium texture, and silty and sandy.

A poorly preserved microflora is present from Cores 7 (1369-1373 m), 8 (1388-1390 m), and 9 (1477-1479 m); it indicates a general Early Carboniferous age (Fowler *in* WAPET, 1962). Although fossiliferous beds are mentioned in the lithological description of the cores in the original unpublished report, no report on the macrofauna has been produced.

The major difference in this interpretation of Langoora No. 1 Well is the recognition of the Yellow Drum Sandstone and the Gumhole Formation in the interval which had been called the Fairfield Formation equivalent. The Laurel Formation boundaries are unchanged.

May River No. 1

The May River No. 1 Well is located at 17°14'50"S, 124°05'01"E, about 48 km due east of Derby (WAPET, 1967). It lies about 7 km north-northeast of Langoora No. 1, and 130 km northwest of the Fairfield Group type sections. The well was spudded in thick alluvium overlying Triassic Blina Shale; the Fairfield Group was intersected between 1172 m and 1579 m.

The Gumhole Formation is 76 m thick and comprises limestone, dolostone, and minor shale. The limestone is light to medium grey-brown, brown, and grey, with a fine to coarse granular texture and occasional pockets of shell fragments; it grades into both dolostone and shale.

The dolostone is medium red-brown, light grey and brown, or geen to grey in colour; it is microcrystalline although locally granular. The siltstone is red-brown and grey, finely micaceous and it grades into both limestone and dolostone. There are thin interbeds of laminated dark grey and green-grey shale.

Fossils are common in some beds including foraminifers, ostracods, crinoid ossicles, brachiopods, pelecypods, and fish. Rare but well preserved spores and acritarchs have been recovered from Core 5 (1511-1515 m) and indicate a latest Devonian or earliest Carboniferous age (Balme *in* WAPET, 1967).

The Yellow Drum Sandstone comprises 101 m of interbedded sandstone and dolostone, with minor limestone and siltstone, in the interval 1402-1503 m. The quartz sandstone is off-white, pale grey, green or greenish-grey, friable to hard, fine to coarse-grained, with a white to light green argillaceous matrix. It is generally non-calcareous and non-dolomitic. The dolostone is light grey, green, brown, and off-white, microcrystalline with scattered grains of quartz. Thin red-brown and green-grey siltstone and shale beds are present in places. The only fossils recovered are plant tissue and rare spores.

The Laurel Formation consists of two members, a 150 m lower limestone member intersected between 1252 m and 1402 m, and an 80 m upper shale member between 1172 m and 1252 m. The lower member consists of interbedded limestone and sandstone with minor siltstone and shale. The limestone is grey to grey-brown, and contains abundant fossil fragments cemented by clear spar. Fine to coarse-grained quartz grains are locally abundant.

The sandstone is white to light grey, firm to moderately friable, slightly micaceous with a calcareous cement; in places it grades to sandy limestone. The siltstone is dark grey to black, sandy, very micaceous; the shale is micaceous and black.

Fossils include brachiopods, pelecypods, gastropods, crinoids, spores and acritarchs. The latter two groups suggest an Early Carboniferous age, but the evidence is equivocal.

The upper member comprises interbedded siltstone and sandstone with a few carbonate beds. The siltstone is grey and green-grey, moderately firm to soft, sandy, micaceous, and calcareous.

The sandstone is white to grey and fine-grained, silty, micaceous, and calcareous, grading into sandy limestone; rarely it contains abundant pyrite. No fossils have been reported from this unit.

The four lithological units which we consider to belong to the Fairfield Group were recognized by WAPET (1967) and referred by them to the Fairfield Formation (sensu Playford & Lowry, 1966). There are minor differences in boundary positions but, in general, the Gumhole Formation is equivalent to their Unit D, the Yellow Drum Sandstone to Unit C, the lower member of the Laurel Formation to Unit B and the upper one to Unit A.

Meda No. 1

The Meda No. 1 Well is situated at 17°24'00"S, 124° 11'30"E, 56 km east of Derby (WAPET, 1962b). The nearest wells are Langoora No. 1, 15 km to the northwest, and Blackstone No. 1, 27 km to the southeast. Meda No. 1 is about 125 km northwest of the type sections of the Fairfield Group. The well was spudded in Triassic Blina shale and the Fairfield Group was intersected in the interval 1503-2018 m.

The Gumhole Formation is 371 m thick and overlies the Devonian reef complex at 2018 m. The unit is dominantly limestone, light grey-brown to cream and red-grey, in part oolitic, with a clear calcite cement. Fine subangular to subrounded quartz grains are present, in places in sufficient quantity to form a sandy limestone.

Fossils are present, though never abundant, and include ostracods, conodonts, and algae. The fauna suggests a latest Devonian age.

The Yellow Drum Sandstone is present in the interval 1623-1649 m and consists of 26 m of interbedded sandstone and sandy dolostone.

The Laurel Formation consists of a lower limestone member and an upper, sandy siltstone member. The lower member is 49 m thick and comprises limestone and siltstone with minor shale and sandstone. The limestone is grey and brown with often abundant quartz grains; the siltstones are dark grey and micaceous and in places grade into black shale. Fossils, including brachiopods, ostracods, conodonts, pelecypods and fish, are abundant. The conodonts, ostracods, and brachiopods all indicate an Early Carboniferous age (Glenister & Furnish; Jones; Thomas, all *in* WAPET, 1962b).

The original interpretation of the Fairfield Group interval by WAPET (1962b) differs from our interpretation in that the Yellow Drum Sandstone and 23 m of Gumhole Formation were included in the lower member of the Laurel Formation, otherwise the boundaries between units are identical.

Napier No. 1

The Napier No. 1 Well is situated 100 km east-northeast of Derby at 17°12'20"S, 124°31'36"E (Lennard Oil, 1969a). The nearest wells are Hawkstone Peak No. 1, about 11 km west-southwest, and Napier No. 5, about 12 km to the northwest; the type sections of the Fairfield Group are 110 km to the southeast. The well was spudded in Carboniferous claystone which may be an equivalent of the Anderson Formation; the Fairfield Group was intersected between 203 m and 832 m.

The Gumhole Formation is 172 m thick and consists of interbedded limestone and dolostone with siltstone and minor shale. The limestone is brown to white, and contains shell fragments and abundant quartz grains. The dolostone is light brown to white; in a few places it is very sandy and grades into dolomitic limestone. The siltstone and shale are either grey-green or brown, fissile, soft, and intermittently calcareous. Fossils are present and include spores, ostracods and conodonts. All groups suggest a Famennian, probably late Famennian age (Balme *in* Lennard Oil, 1969a; Jones *in* Lennard Oil, 1969a).

The Yellow Drum Sandstone was intersected between 333 m and 660 m and consists of 327 m of siltstone with minor sandstone in the interval 333-377 m, and claystone with minor dolostone in the interval 377-660 m. The siltstone is grey-green, sandy, fissile, chloritic and calcareous; the sandstone is pale white and very fine-grained. The claystone is light grey-green, and slightly calcareous; it is interbedded with grey-green micaceous siltstone, and, towards the base, light brown to brown silty dolostone.

The Laurel Formation consists of an upper siltstone member and a lower limestone member. The lower member is 36 m thick and consists of a grey, brown, sandy fossiliferous limestone overlying a tan to white oolite, cemented with white sparry calcite. Fossils have been recovered from core 1, (204 m) and both the spores and the questionable alga *(Umbella)* suggest a latest Devonian age (Balme *in* Lennard Oil, 1969a; Jones, *ibid*); the evidence is not conclusive and an earliest Carboniferous age cannot be excluded, although the presence of *Leiozonotriletes naumovae* Balme & Hassell (=*Hymenozonotriletes lepidophytus* Kedo) strongly suggests latest Late Devonian (Strunian, tnla).

Napier No. 1 Well has proved difficult to interpret; the sequence is extremely thick with a large influx of fine clay and silt. An alternative interpretation to that presented above is that all the sequence between 203 m and 832 m is equivalent to the Gumhole Formation and the upper 200 m of the sequence, which consists of siltstone, shale, coarse sandstone, and claystone, is equivalent to the Yellow Drum Sandstone. The section in Station Creek immediately to the north and east shows a thin limestone unit (=Laurel Formation) overlying massive sandstone interbedded with siltstone (=Yellow Drum Sandstone) which, in turn, overlies a thick sequence of siltstone with thin beds of brown to grey fossiliferous limestone; this sugggests that the former interpretation is correct. However, evidence from Napier Nos. 2 and 5 suggests rapid and considerable facies changes in the Fairfield Group in the immediate vicinity of Station Creek, and this either interpretation is possible.

Napier No. 2

The Napier No. 2 Well is located at 17°04'55"S, 124° 21'20"E, 80 km northeast of Derby. The nearest wells are Napier No. 5 about 15 km to the east-southeast, and Hawkstone Peak No. 1, 20 km to the south-southeast. The Fairfield Group type sections are 140 km to the southeast.

The well was spudded in a 147 m sandstone unit of unknown age which overlies Frasnian sediments (Jones *in* Lennard Oil, 1969b, and pers. comm.). The sandstone could be a nearshore lateral equivalent of the Laurel Formation. Conversely it is possible the younger Anderson Formation.

Napier No. 4

The Napier No. 4 well is located at 16°15'00"S, 124° 55'35"E, 70 km northeast of Derby. The nearest wells are Napier No. 2, 32 km to the southeast, and May River No. 1, 40 km to the south; the Fairfield Group type sections are 170 km to the southeast.

The well was spudded in a thin sequence (10 m) of aeolian sand overlying probable Permian Grant Formation; the Fairfield Group was intersected between 68 and 220 m.

The Gumhole Formation is only 4 m thick, and consists of a calcareous unit (referred to as marl by Lennard Oil, 1970a) which is mottled grey-green and buff with interbedded green calcareous claystone. The unit has yielded ostracods (Jones *in* Lennard Oil, 1970a) and spores (Balme *in ibid.*) which indicate a late Famennian age.

The remainder of the Fairfield Group consists of 148 m of Yellow Drum Sandstone in the interval 68-216 m. The unit is predominantly sandstone, white, yellow, and pink to red, medium to very coarse, friable and grading to pebbly conglomerate. The sandstone is interbedded with thin, red to red-brown and light green, variegated silty claystone.

Spores are the only fossils which have been recovered from this interval (Balme *in* Lennard Oil, 1970a). They are Early Carboniferous and are known from the Laurel Formation. Balme (*ibid.*) notes that within the interval there are very marked quantitative differences between the assemblage at 385' (117 m) and 394' (120 m). These must be mainly attributable to ecological causes and suggest a marginal environment subject to rapid, and probably localised, floral modifications. It is likely that the spore assemblages represent plant associations growing in deltaic swamps or river flood plains, which responded critically to relatively minor changes in water-table conditions.

Our interpretation differs slightly from that of Lennard Oil (1970a). We consider that a small part of the Fairfield Formation equivalent is referrable to the Gumhole Formation and that below 220 m it is probably equivalent to the Luluigui Formation. The dominantly sandstone part of Lennard Oil's Fairfield Formation equivalent between 169 m and 216 m is placed in the Yellow Drum Sandstone, as is all of their Laurel Formation.

Napier No. 5

The Napier No. 5 well is situated at 17°06'30"S, 124°28'06"E, 90 km east-northeast of Derby (Lennard Oil, 1970b). The nearest wells are Napier No. 1, 12 km to the south-southeast, Hawkstone Peak No. 1, 16 km to the south-southwest, and Napier No. 2, 15 km to the west-northwest. The type sections of the components of the Fairfield Group are some 120 km to the southeast.

The well was spudded in a sandstone of unknown age, possibly equivalent to the Anderson Formation; the Fairfield Group was intersected between 49 m and 198 m, only the Gumhole Formation and the Yellow Drum Sandstone being penetrated.

The Gumhole Formation is 121 m thick with a base at 198 m. The unit consists of interbedded shale, limestone, siltstone, and rare sandstone. The dominant lithology varies through the sequence, consisting of shale (173 m — 198 m), limestone (154 m — 173 m), shale (123 m — 154 m), limestone (111 m — 123 m), and shale (77 m — 111 m). The limestone is thick bedded, white, light brown, red and yellow, and fossiliferous with occasional coquinities; the shale interbeds are brown, grey-green to light brown, fissile and fossiliferous.

The shale is grey-green to grey, fissile, partly micaceous and silty with few fossils; the interbedded limestone is light brown to grey brown, thickly bedded, silty and fossiliferous.

Within the unit the alga *Umbella* is extremely abundant; ostracods are also common and represent a typical assemblage from the Gumhole Formation in the type area (Jones *in* Lennard Oil, 1970b).

The Yellow Drum Sandstone is present in the interval 49 m — 77 m and consists of dominant siltstone with interbedded shales and sandstones. The siltstones are multicoloured and variegated, shaly to sandy, in places calcareous and finely micaceous. The shale is light green to red-brown, silty to sandy, micaceous and partly calcareous. The sandstone is thin, white to light green, fine to very coarse-grained, poorly sorted and friable.

Rare and poorly preserved ostracods below 55 m are the only fossils reported; they suggest a late Famennian age.

The limits of the Yellow Drum Sandstone have been drawn so as to exclude limestone beds. Thus the lower 6 m of Lennard Oil's Anderson and Laurel Formation has been included in the Gumhole Formation, and the upper 49 m (from 0–49 m) has been excluded. This interval is of unknown age; it is either a lateral equivalent of the Laurel Formation or part of the younger Anderson Formation. No fossils have been recovered.

BMR Noonkanbah No. 2

The BMR Noonkanbah No. 2 Well (formerly known as Laurel Downs No. 2) is situated at 18°07'24"S, 125°19'58"E, about 27 km northwest of Fitzroy Crossing (Henderson & Condon *in* Henderson *et al.*, 1963). It is the closest well to the type section of the Fairfield Group, being 10 km west-southwest of the Gumhole type section, 19 km southwest of the Yellow Drum Sandstone type section, and from 15 to 22 km southeast of the Laurel type section. The nearest wells are Palm Springs No. 1, 58 km to the northwest and situated on the Lennard Shelf, and St George Range No. 1 (in which the Fairfield Group was not intersected) 68 km to the south-southwest in the Fitzroy Trough.

The well was spudded in Quaternary sand overlying probable Permian Grant Formation. The Fairfield Group was intersected between 76 and 567 m and consists of the Gumhole and Laurel Formations and the Yellow Drum Sandstone.

The Gumhole Formation is 27 m thick and overlies Luluigui Formation equivalent at 567 m. It consists of interbedded limestone, sandstone and shale; the limestone is pale brown, laminated, fine to medium-grained with abundant fossils; the sandstone is pale, fine to medium-grained, slightly calcareous and fossiliferous.

The fossils recovered include ostracods (Jones, 1959; *in* Veevers & Wells, 1961) and spores (Balme & Hassell, 1962). The ostracods are identical to faunas recovered from outcrops of the Gumhole Formation.

The Yellow Drum Sandstone consists of 107 m of sandstone and dolostone with minor shale, siltstone and dolomitic limestone. The sandstone is light brown to greenish-grey, fine to medium grained and occasionally calcareous. The dolostone is dark greyish-brown to brown and fine to medium-grained. The shale and siltstone are dark grey with lignite fragments. No fossils have been reported from this sequence.

The Laurel Formation consists of two members in the interval 76 m-433 m; a 189 m lower limestone member and a 168 m upper shale member. The lower member consists of pale grey to brown and white limestones which are laminated and have scattered quartz grains; they are occasionally oolitic and shelly. Interbedded are dark grey siltstones, pale green shale and rare beds of hard white coarse sandstone.

The upper member is dominantly calcareous siltstone and silty limestone with interbedded shale and sandstone. The calcareous siltstones are fossiliferous, pale brown to dark grey, occasionally micaceous, with rare quartz grains. The sandstones are pale grey, laminated and very fine grained; the limestones are white to grey, medium to coarse grained and fossiliferous.

A diverse fauna has been reported from the Laurel Formation including brachiopods (Jones, 1959, Thomas, 1962), ostracods (Jones, 1959; Jones *in* Veevers & Wells, 1961), conodonts (Glenister, 1960), crinoids (Henderson & Condon *in* Henderson *et al.*, 1962), fish (Jones, 1959; Thomas, 1962), and bryozoans (Thomas, 1962). All these groups indicate an Early Carboniferous (Tournaisian) age for the Laurel Formation.

This interpretation differs from that of Henderson & Condon (1962) in that we recognize the Yellow Drum Sandstone in an interval placed by them in the Fairfield Beds (*sensu* Guppy *et al.*, 1958). The boundaries of the Laurel Formation are unchanged, although the palaeontological evidence suggests that some of the overlying rocks are of similar age to the Laurel Formation and should perhaps be regarded as a regressive unit (?member) of the Laurel Formation.

Palm Spring No. 1

The Palm Spring No. 1 Well is situated at 17°48'56"S, 124°53'8"E, about 145 km east-southeast of Derby and 85 km northwest of Fitzroy Crossing. It is about 45 km northwest of the type sections of the Fairfield Group; the nearest well is BMR Noonkanbah No. 2, 58 km to the southeast.

The well was spudded in Quaternary soil overlying Permian Noonkanbah Formation and intersected the Fairfield Group in the interval 462–655 m. This interval is referrable to the Gumhole Formation, and consists of limestone with interbedded claystone, shale, siltstone and sandstone. The limestone is white to light brown and grey, and massive; it is oolitic, intraclastic, and sandy in part. It grades into calcareous light grey to green-grey siltstone which is laminated, massive and micaceous. The shale and claystone are light to dark grey; the sandstones are light to dark grey, orange-brown, medium to coarse, loosely packed in a hard calcareous clay-silt matrix.

Fossils are rare; late Famennian conodonts are reported from cuttings between 521–524 m, and indeterminate shells from cuttings between 643–646 m.

Overlying the Gumhole Formation is a sandstone unit succeeded by a sequence of interbedded limestone, shale, siltstone and sandstone. Sidewall cores at 418 m have yielded a Permian microflora, and WAPET (1972) have interpreted the sequence above 462 m as Permian Grant Formation. The seismic results show possible relief of up to 150 m on the pre-Permian unconformity, the implication being that Palm Spring No. 1 was drilled on a pre-Permian topographic low within which all the Laurel Formation and Yellow Drum Sandstone had been eroded. The limestones at the base of WAPET's Grant Formation are presumed to be reworked Devonian rocks. Sidewall cores taken at 440 m, 450 m, and 466 m have yielded spores which suggest an equivocal Permian age.

An alternative interpretation is that the sandstone between 436 and 462 m represents the Yellow Drum Sandstone; and the 37 m of interbedded sandstone and white to light brown sandy limestone with bioclasts of bryozoans and small brachiopods, represents the Laurel Formation.

FITZROY TROUGH AND JURGURRA TERRACE

Lake Betty No. 1

The Lake Betty No. 1 Well is situated at 19°34'08"S, 126°19'45"E, about 210 km southwest of Halls Creek (WAPET, 1972). The nearest well, St George Range No. 1, is 200 km to the northwest.

The well was spudded in Permian Liveringa Formation and intersected the Fairfield Group between 1657 m and 2558 m. The 49 m thick Gumhole Formation occurs between 2509 and 2558 m, and consists of limestone and siltstone with thin interbeds of sandstone. The limestone is medium to dark brown, silty and dense; the siltstone is light to medium grey, partly sandy, commonly micaceous; it graded into very fine-grained sandstone. No fossils have been recovered from this interval.

The Yellow Drum Sandstone is 52 m thick and consists of light grey medium-grained sandstone with minor light grey shale and siltstone. Fossils from this interval include spores which indicate marine conditions at 2462 m, but furnish no evidence of a marine environment at 2475 m and 2498 m (Williams & Dolby *in* WAPET, 1972), and indeterminate ostracods and gastropods (Jones *in ibid*).

The Laurel Formation extends from 2475 to 1657 m and consists of a lower limestone member and an upper shale and siltstone member. The 151 m thick lower member consists predominantly of light to dark brown grey-brown finely crystalline, silty and argillaceous, fossiliferous limestone. Interbedded is grey-brown to green-grey siltstone, which grades to very fine sandstone. The upper member consists of siltstone and shale with a few thick beds of sandstone and limestone. The siltstone is grey to grey-brown, argillaceous, micaceous, slightly calcareous and interbedded with light to dark grey, slightly calcareous shale. The minor limestone is cream to brown, finely crystalline and fossiliferous. The sandstone is white to light grey, very fine to fine-grained, in places calcareous and locally micaceous. Fossils include crinoids, pelecypods and brachiopods (WAPET, 1972), spores (Williams & Dolby *in ibid*), ostracods (Jones *in ibid*), and conodonts (McTavish *in ibid*). The flora and fauna indicate a Tournaisian age.

WAPET (1972) interpreted the sequence somewhat differently; they consider that all the sequence from 1657 to 2558 m is Laurel Formation, whereas we recognize both the Gumhole Formation and Yellow Drum Sandstone in the lower part of this interval.

St George Range No. 1

The St George Range No. 1 Well is at 18°41'30"S, 125°8'11"E, 70 km southwest of Fitzroy Crossing and 225 km southeast of Derby. The nearest wells are BMR Noonkanbah No. 2, 68 km to the north-northeast and Lake Betty No. 1, 155 km to the southeast; the Fairfield Group type sections are some 80 km to the north-northwest. The well intersected at least 1951 m of Carboniferous sediments, of which the lower 1554 m was interpreted as Laurel Formation. This interval was divided into three informal units, the lowest of which consists of siltstone and mudstone. The middle unit is also dominated by siltstone and mudstone with minor dolostone rather than limestone as in the lower unit. The upper unit consists of sandstone, siltstone, shale and dolomite.

The exact age of this interval (2884 m — 4438 m) is equivocal: the spores (Balme *in* Continental Oil, 1965) are interpreted as being post-Visean and therefore Upper Carboniferous, whereas one ostracod species (*Cryptophyllus diatropus*) is present in the Laurel Formation and a second (*Cryptophyllus* sp. B) is known from the younger Anderson Formation (Jones *in ibid*).

Lithological comparison with the Fairfield Group is not possible although the basal sequence (unit C, 3984 m — 4438 m) may be equivalent to the upper shale and siltstone member of the Laurel Formation. This implies that units B and A lie between the Laurel Formation and the Anderson Formation.

Doran No. 1

The Doran No. 1 corehole is at 18°10'56"S, 123°29'06"E, 100 km south of Derby. The nearest wells are Frome Rocks No. 2, 15 km to the east-southeast, and Yulleroo 70 km to the northwest (WAPET, 1968).

The well failed to intersect the Fairfield Group; Permian Grant Formation directly overlies the Luluigui Formation. The age of the Luluigui Formation in this corehole is that of the Gumhole Formation in the type area and the two formations are, in part, coeval.

Frome Rocks No. 2

The Frome Rocks No. 2 Well is at 18°11'48"S, 123°38'42"E, 100 km due south of Derby (WAPET, 1962c). The nearest wells are Doran No. 1, 15 km to the west-northwest, and Grant Range No. 1 (which did not penetrate deep enough to intersect the Fairfield Group) some 75 km to the northeast. The well is 170 km across the trough from the type sections of the Fairfield Group. The well was spudded in Holocene sand overlying Jurassic Wallal Sandstone; the Fairfield Group was intersected between 1078 m and 1338 m, the Laurel Formation and Yellow Drum Sandstone being absent.

The 260 m of Gumhole Formation consists of interbedded limestone, siltstone, shale, and sandstone. The limestone is grey, brown, and cream, silty and sandy; in places it grades to calcareous siltstone. The shales are green-grey, silty, fissile, slightly calcareous, and rich in ostracods. The minor sandstones are thin bedded, very fine-grained, micaceous with a calcareous cement.

Fossils from the interval include conodonts, fish, ostracods, conchostracans, spores and microplankton. The flora and fauna indicate a late Famennian age (Balme *in* WAPET, 1962c; Glenister, *ibid*; Jones, *ibid*).

Yulleroo No. 1

Yulleroo No. 1 Well is at 17°51'16"S, 122°54'25"E, 100 km southwest of Derby and 75 km east of Broome (Gewerkschaft Elwerath, 1967). The nearest wells are Barlee No. 1, 21 km to the west, which penetrated Lower Carboniferous sediments younger than the Fairfield Group, as did Grant Range No. 1, 120 km to the east-southeast.

The well spudded in Holocene sand overlying Cretaceous Broome Sandstone; the Grant Formation unconformably overlies the Lower Carboniferous at 621 m, and the Fairfield Group was intersected between about 3409 m, and 3963 m.

The Gumhole Formation is 113 m thick and consists of limestone with interbeds of fine-grained sandstone, siltstone, and shale. The limestone is medium to dark grey, silty and argillaceous; the siltstone is grey, grading to fine micaceous and calcareous sandstone. The shale is light grey, silty, micaceous and calcareous. Fossils include echinoderms, foraminifers, conodonts, ostracods, brachiopods and a gastropod.

The Yellow Drum Sandstone extends from 3735 m to 3851 m, is 115 m thick and consists of shale and siltstone with minor sandstone. The shale is blackish-grey to black, partly silty, mostly non-calcareous and fossiliferous. The siltstone is medium grey, micaceous, calcareous and dolomitic, grading to silty shale. The sandstone is light grey, fine-grained, slightly siliceous and calcareous, and contains minute particles of coal. Fossils include conodonts, foraminifers, ostracods, fish, echinoderms, gastropods, and bryozoans; they are early Tournaisian.

The Laurel Formation consists of a lower limestone member, and an upper shale member intersected between 3409 m and 3735 m. The lower member is 68 m thick and consists of light to medium-grey, dolomitic limestone which grades into calcareous siltstone, interbedded with blackish-grey shale. Fossils include conodonts, ostracods, foraminifers, fish, goniatites, brachiopods, gastropods, echinoderms, and bryozoans. The conodonts and ostracods indicate a Tournaisian, possibly late Tournaisian age (Bischoff *in* Gewerkschaft Elwerath, 1967).

The stratigraphic nomenclature was left open by Gewerkschaft Elwerath (1967); the Gumhole Formation was referred to as Upper Devonian, *costatus*-Zone (*sensu* Ziegler, 1962) and the boundary between the Gumhole Formation and the Yellow Drum Sandstone approximates to their boundary between Devonian and Carboniferous.

The Yellow Drum Sandstone and the Laurel Formation are equivalent to the lower 442 m of the 1979 m thick Carboniferous Unit C.

APPENDIX II

PETROGRAPHY OF STRATIGRAPHIC SECTIONS

Shale

Siltstone

Sandstone

Limestone

Sandy
Silty
Shaley

Dolomitic limestone

Calcareous dolostone

Dolostone

Unconformity

Conglomeratic

Breccia, brecciated

Calcareous

Calcareous lens/bed

Dolomitic

Scour and fill

Vertical burrow

Bedding

Thick

Medium

Thin

Laminate

Cross-bedded

Cross-laminated

Undulate

Slumped

Carbonate grain types

P *Pellets*

Ooids

Intraclasts

Skeletal particles

Brachiopods

Pelecypods

Gastropods

Crinoids

Y *Bryozoans*

Coral

Ostracods

Fish

Bar diagrams

Complete particles or angular fragments

Abraded, rounded grains

Bar width is a quantitative approximation of relative abundance of grain types in each sample

Geochemical sample

Geochemical sample and thin section

Photography

Colour

Black and white

Siliciclastic sand

Quantitative weight percent; a generalized curve

Annotations for particles

B	*Broken*
be	*Branching, encrusting*
br	*Branching form*
compl	*Complete*
cpd	*Compound*
dsc	*Discoidal*
eb	*Epibiotic*
el	*Elongate*
encr	*Encrusting form*
F	*Feldspathic*
f	*Fine*
fe	*Fenestrate*
gncv	*Coated valve*
h	*Heavy*
lg	*Large*
m	*Medium*
no syn	*No syntaxial cement rim*
py	*Pyritic infill of pores*
Q	*Quartzose*
RS	*Rugose, Solitary*
r	*Reworked*
Syr	*Syringopora*
s	*Small*
sh	*Shell*
sm	*Smooth*
sp	*Spines*
sph	*Spherical*
sy	*Syntaxial cement rim*
T	*Tabulate*
Tc	*Tabulate, colonial*

AUS 1/625

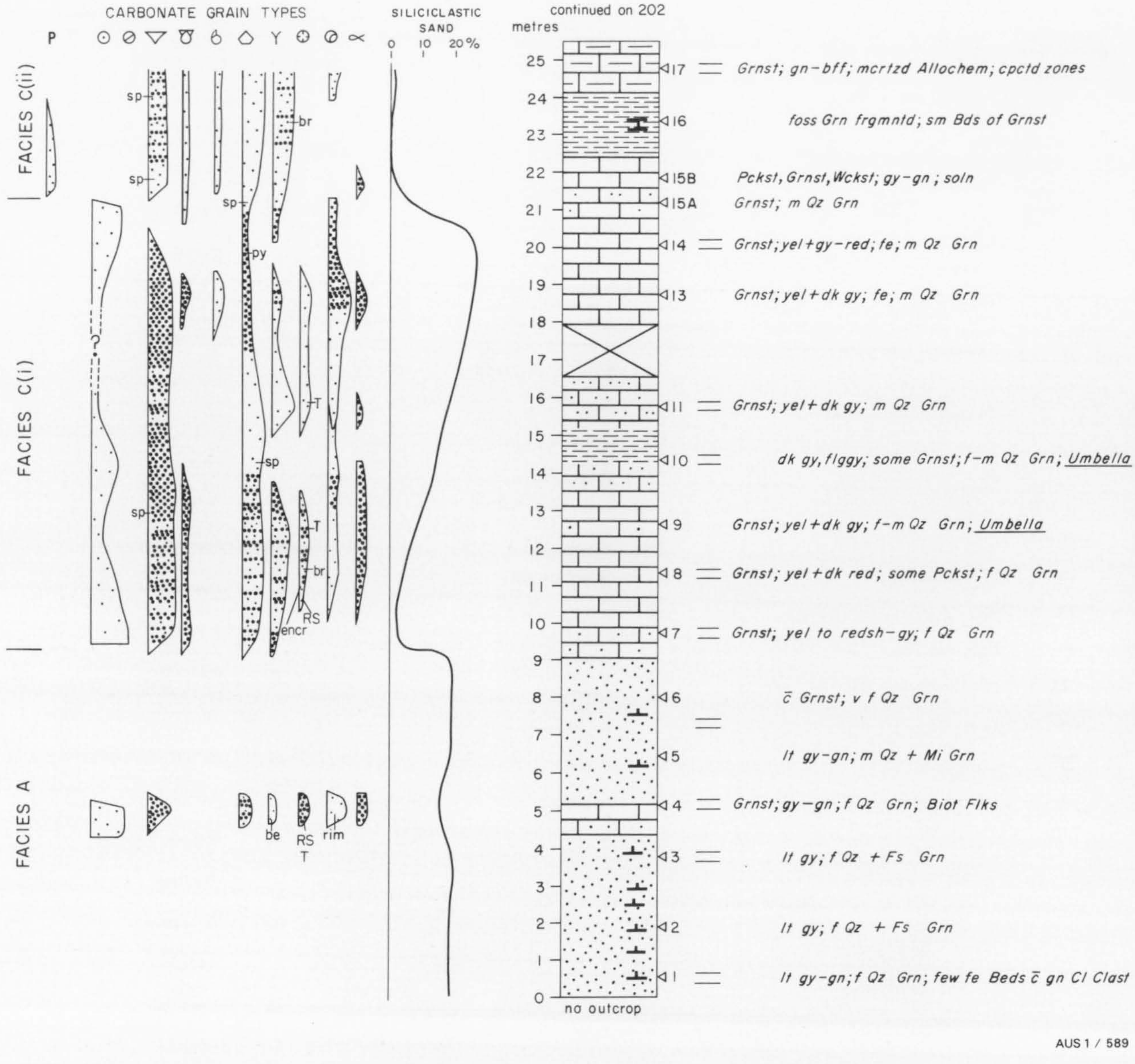

Figure 39. Type Section WCB 001, Gumhole Bore, Gumhole Formation.

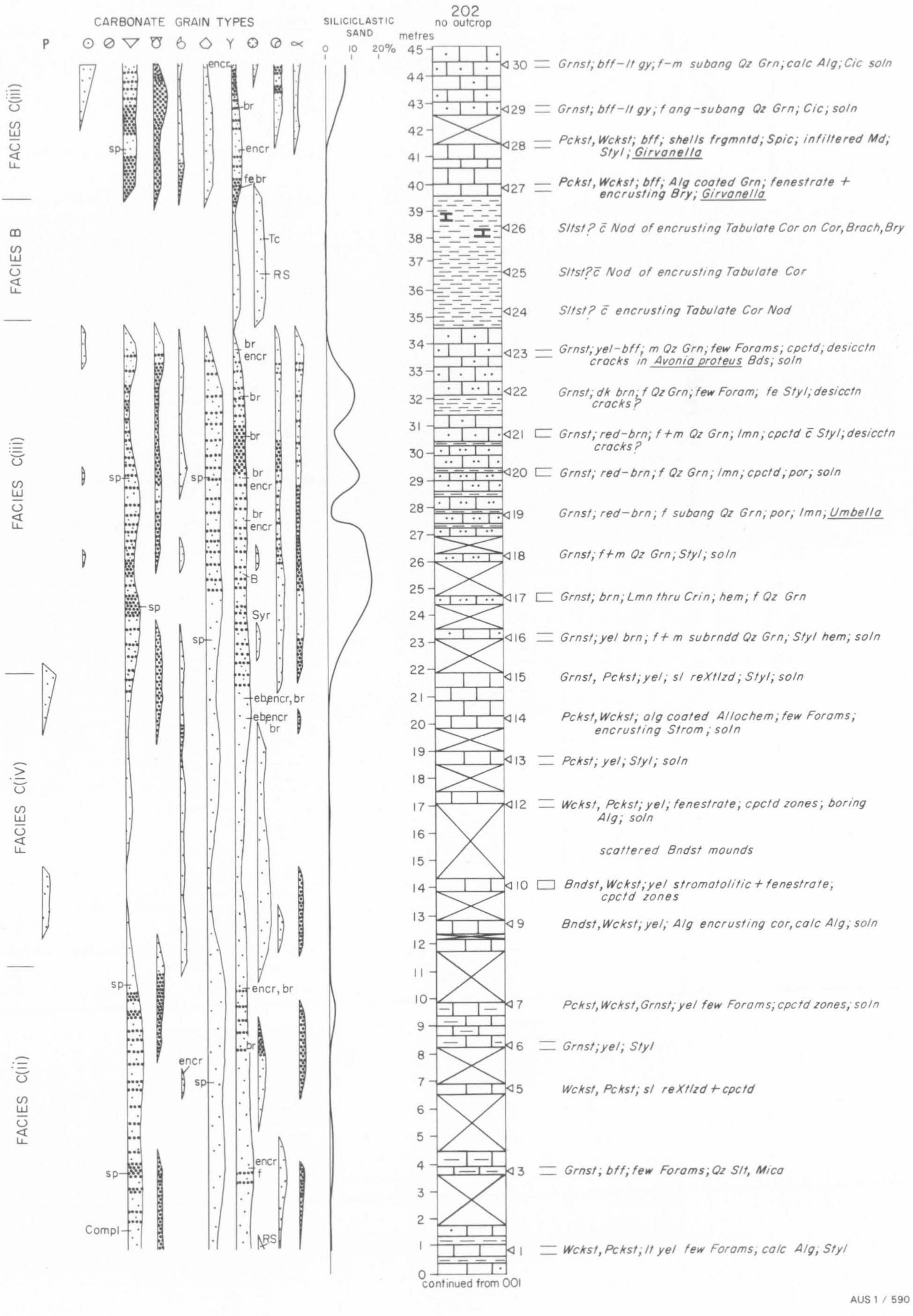

Figure 40. Type Section WCB 202, Gumhole Bore, Gumhole Formation.

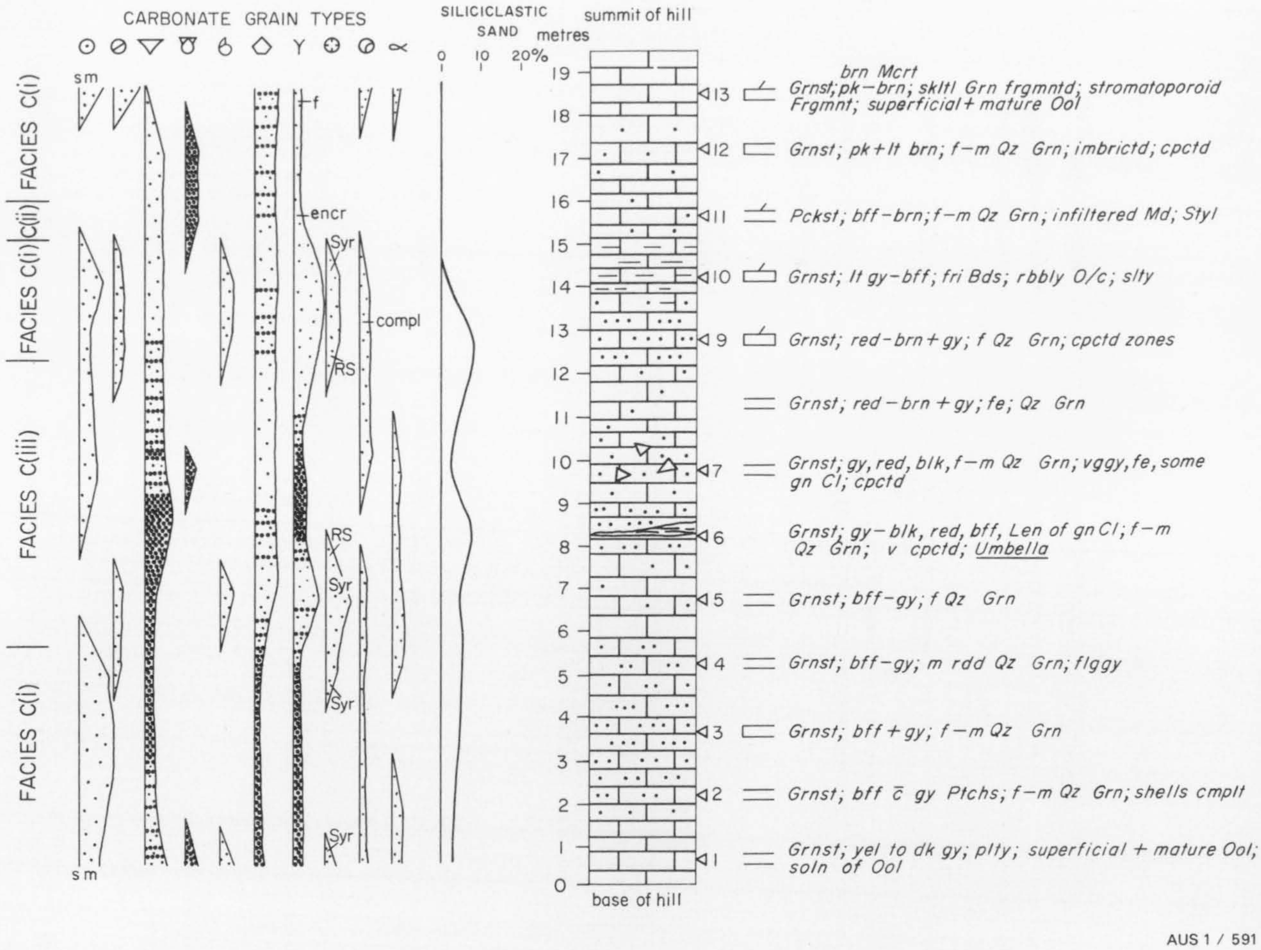

Figure 41. Section WCB 002, Oscar Hill, Gumhole Formation.

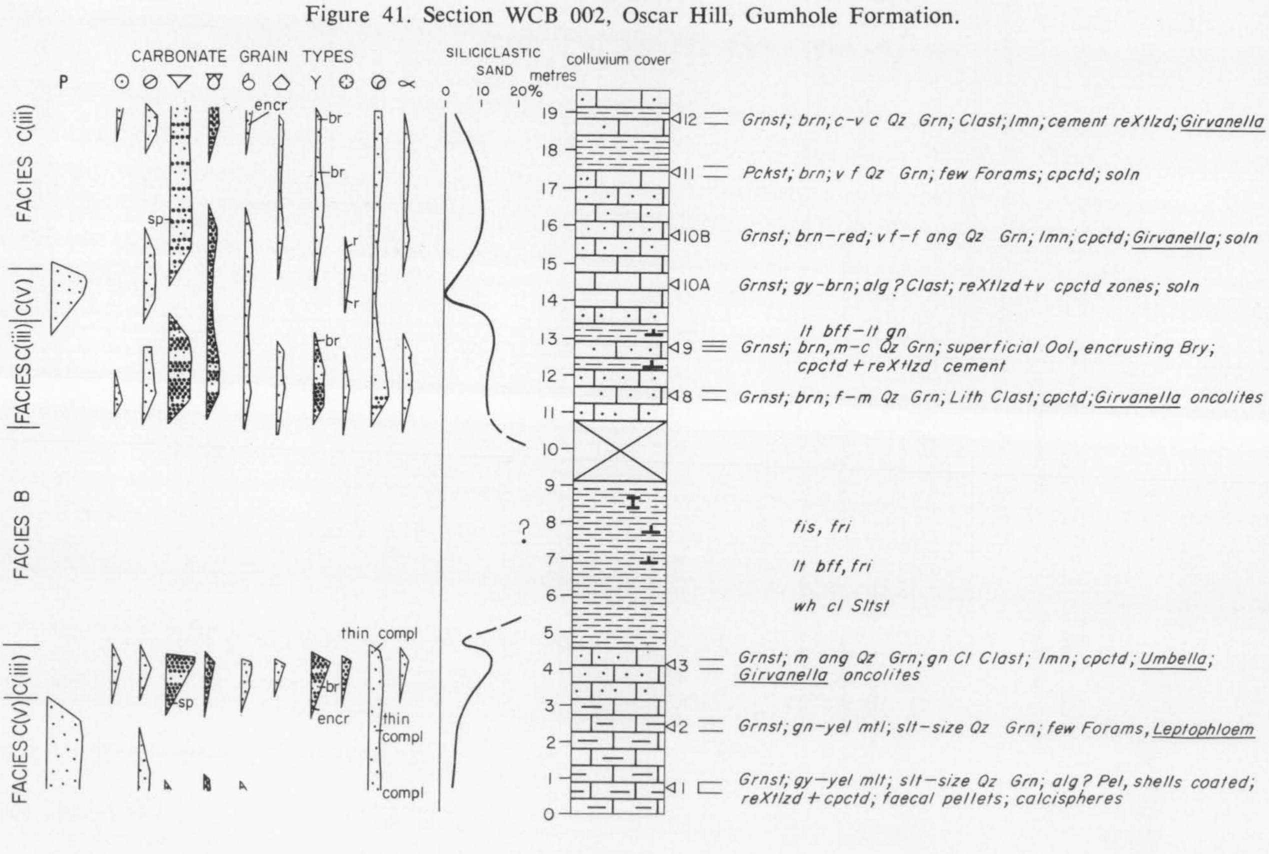

Figure 42. Section WCB 222, Horseshoe Range, Gumhole Formation.

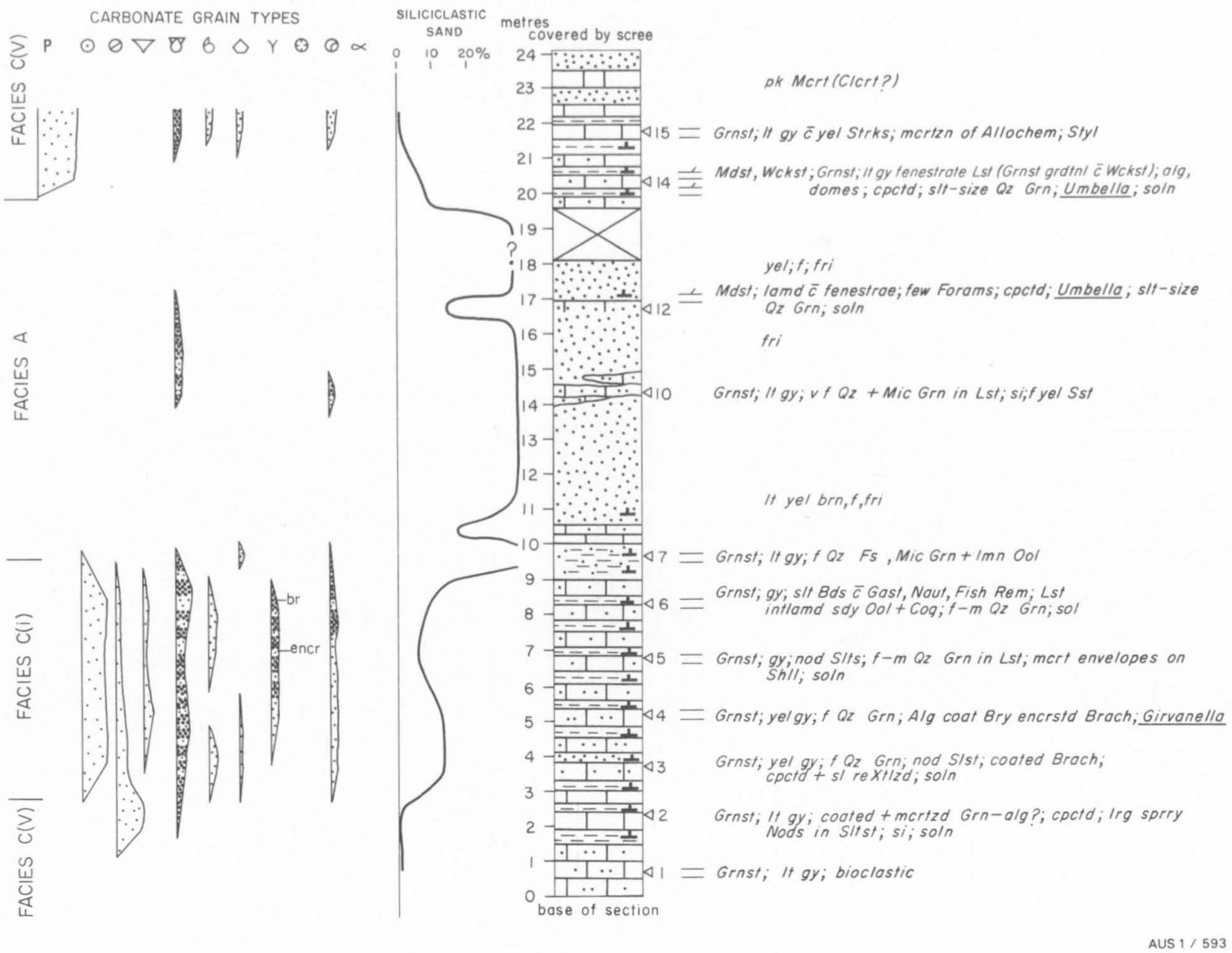

Figure 43. Section WCB 014, Red Bluffs, Gumhole Formation.

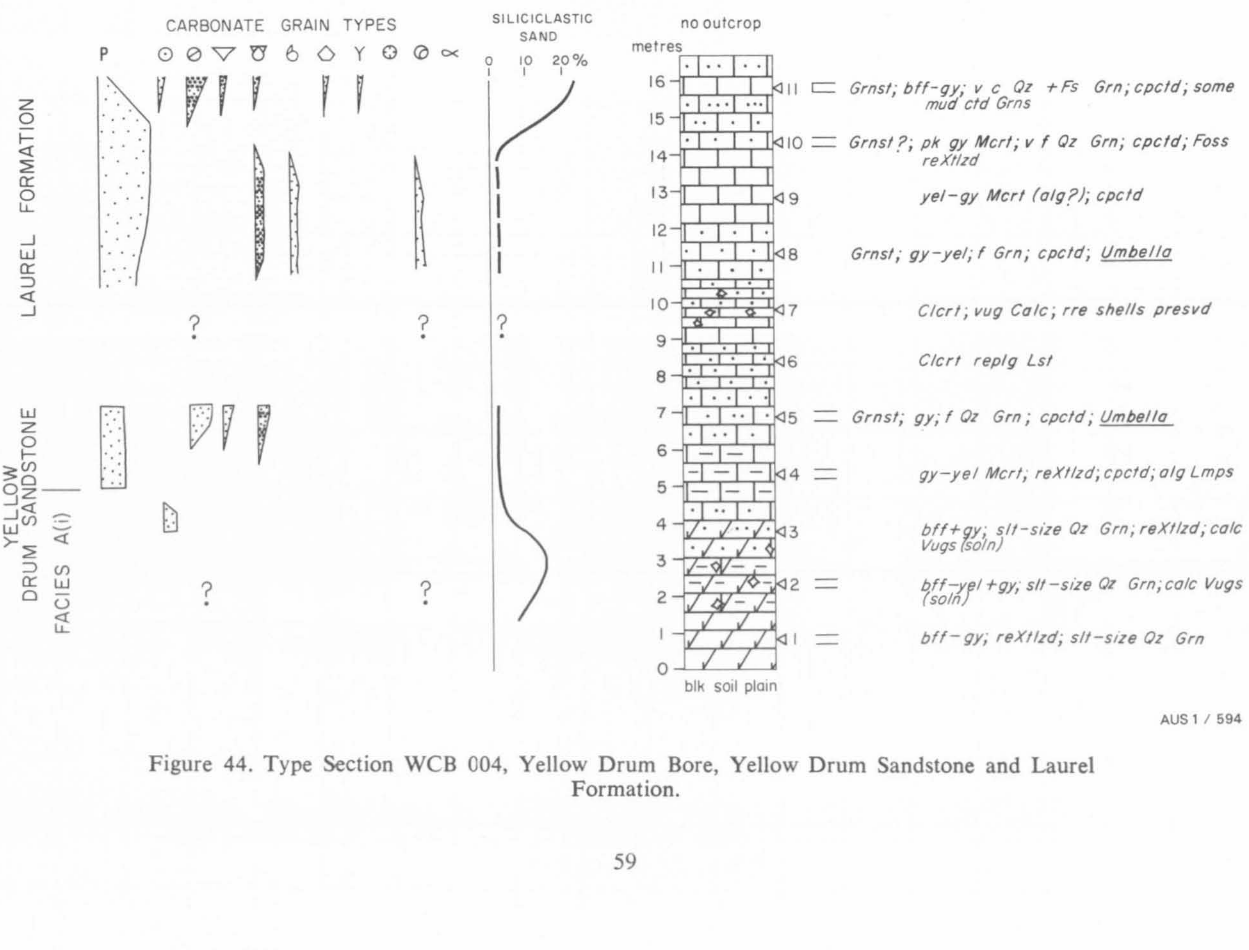

Figure 44. Type Section WCB 004, Yellow Drum Bore, Yellow Drum Sandstone and Laurel Formation.

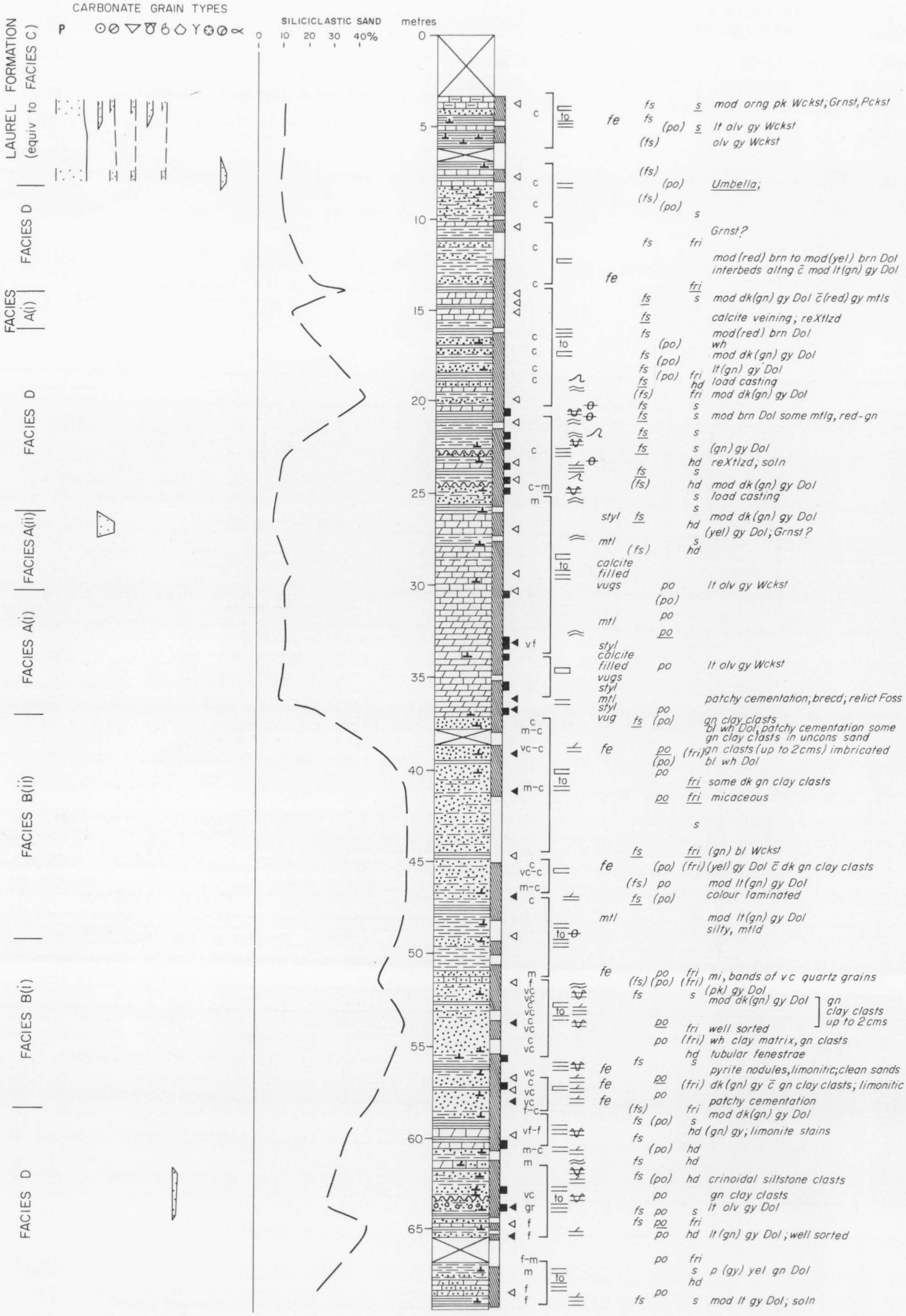

Figure 45. Stratigraphic drillhole BMR Noonkanbah 4, Yellow Drum Bore, Yellow Drum Sandstone and Laurel Formation.

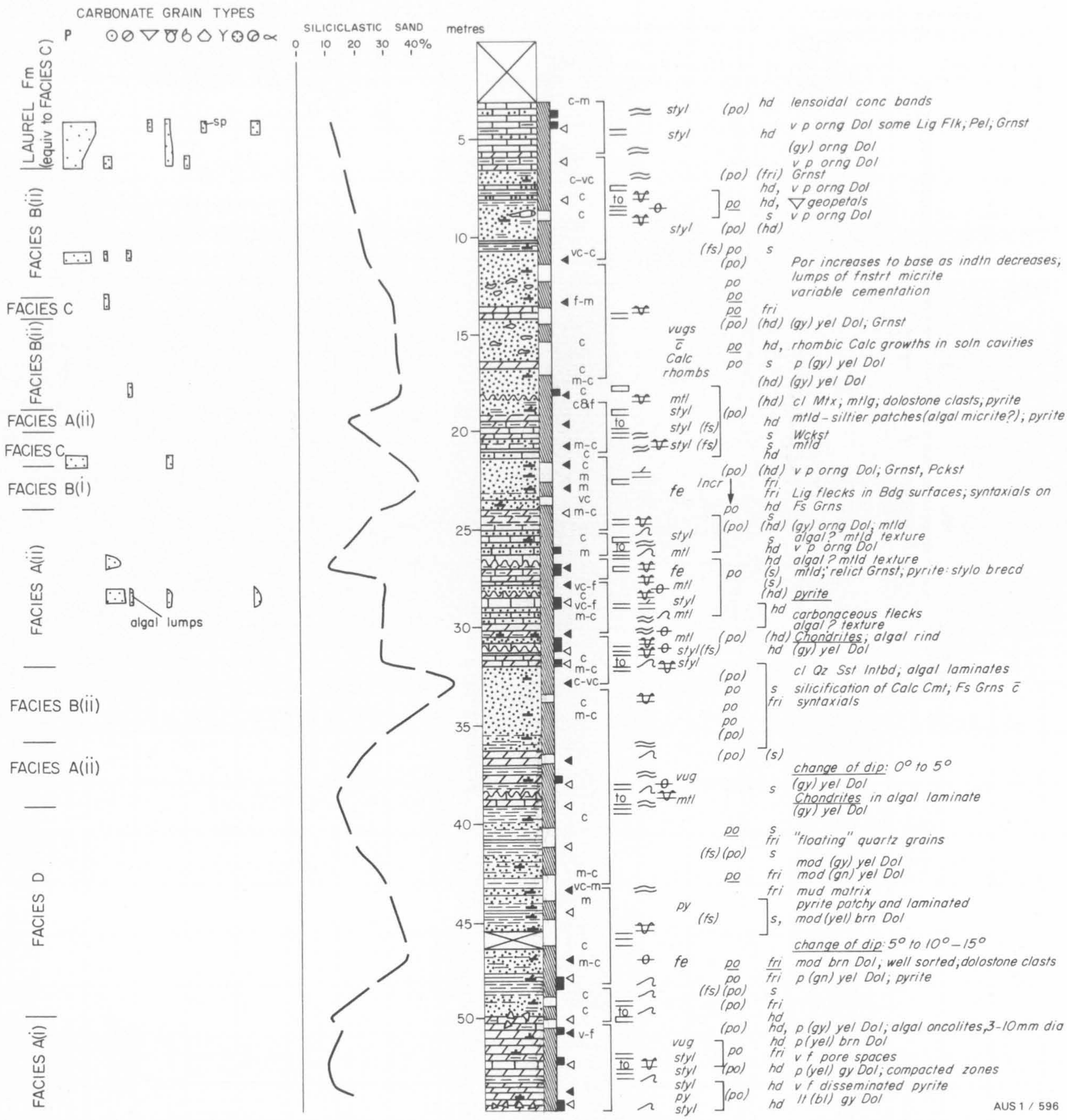

Figure 46. Stratigraphic drillhole BMR Lennard River 1, NW of Twelve Mile Bore, Yellow Drum Sandstone and Laurel Formation.

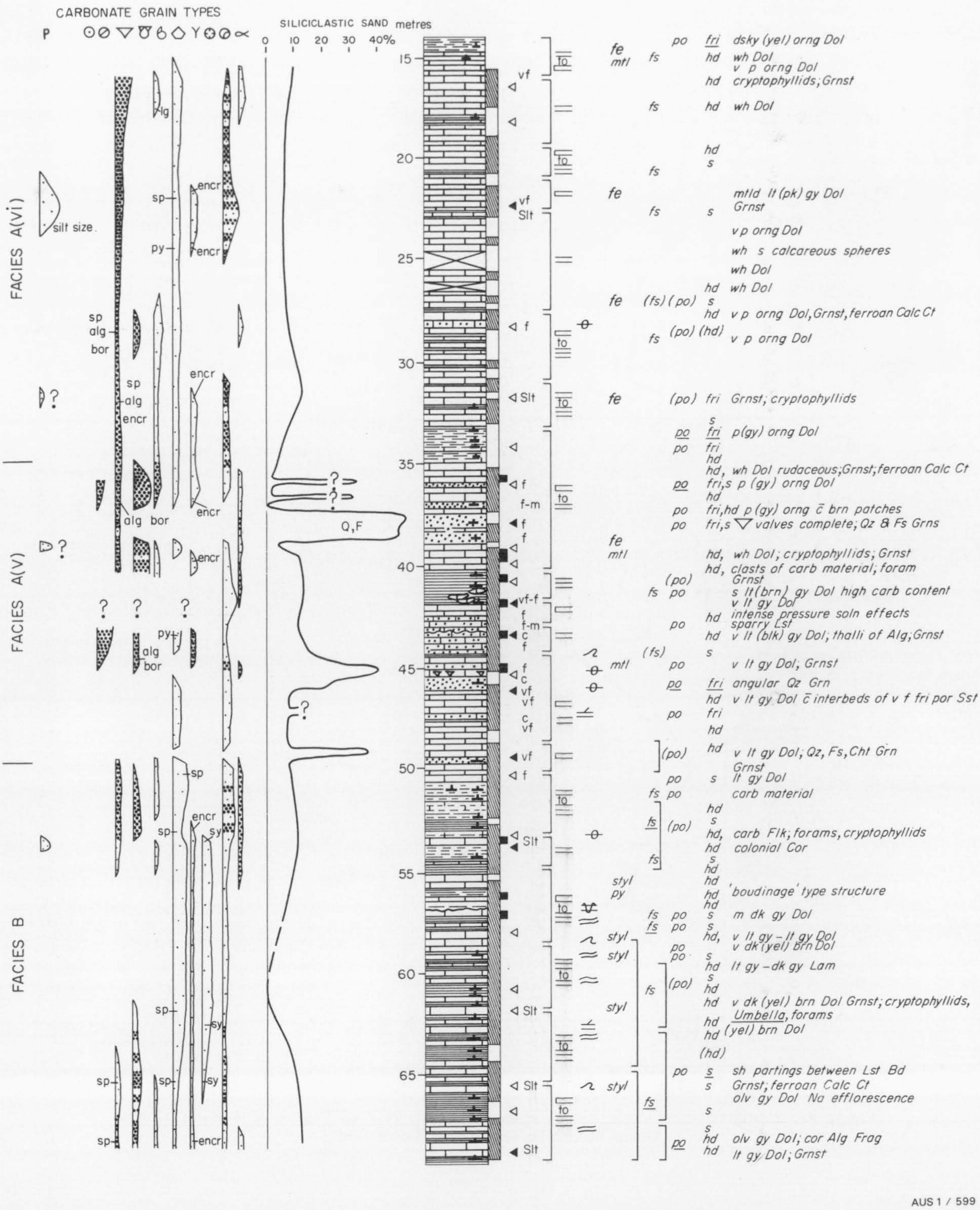

Figure 49. Stratigraphic drillhole BMR Lennard River 2, south of Twelve Mile Bore, Laurel Formation.

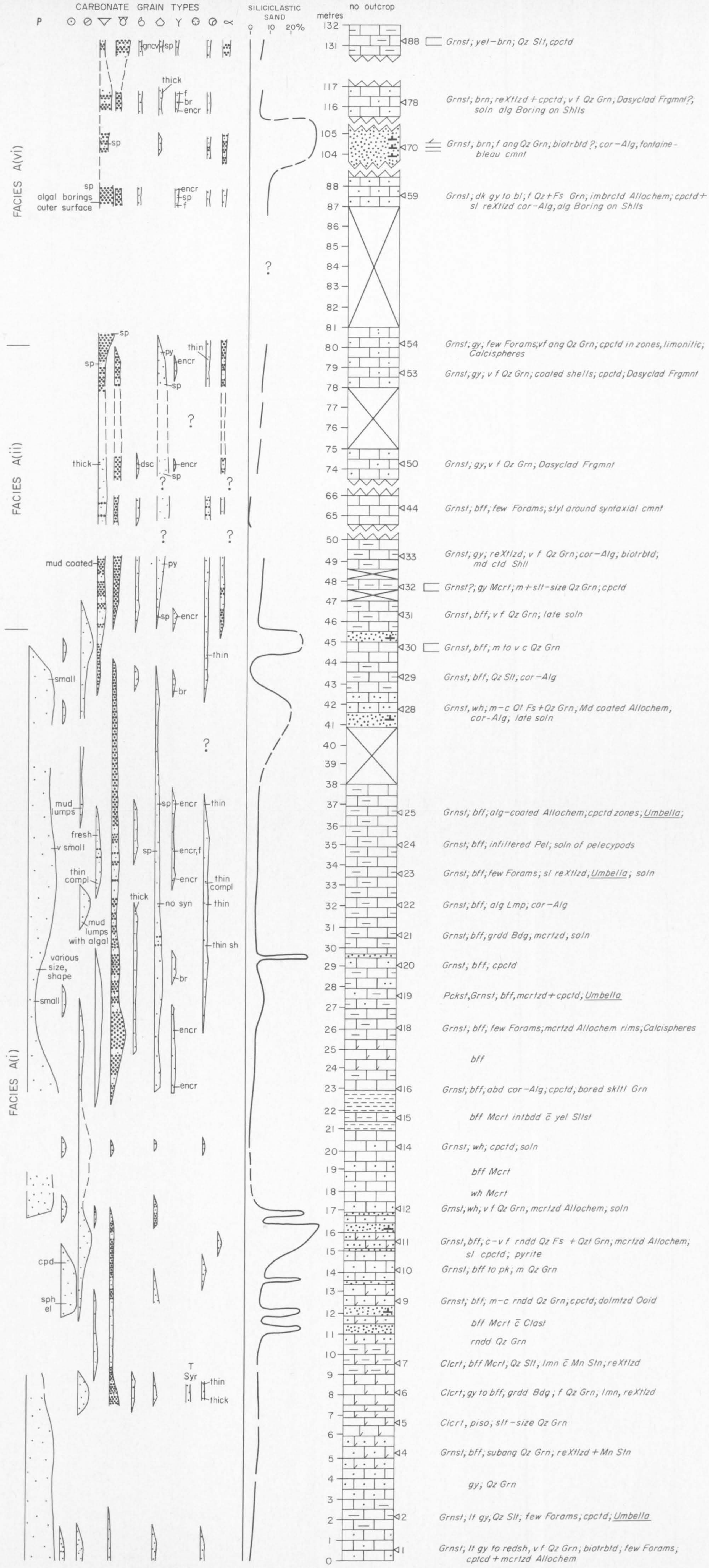

Figure 47. Type Section WCB 101, NW of Twelve Mile Bore, Laurel Formation.

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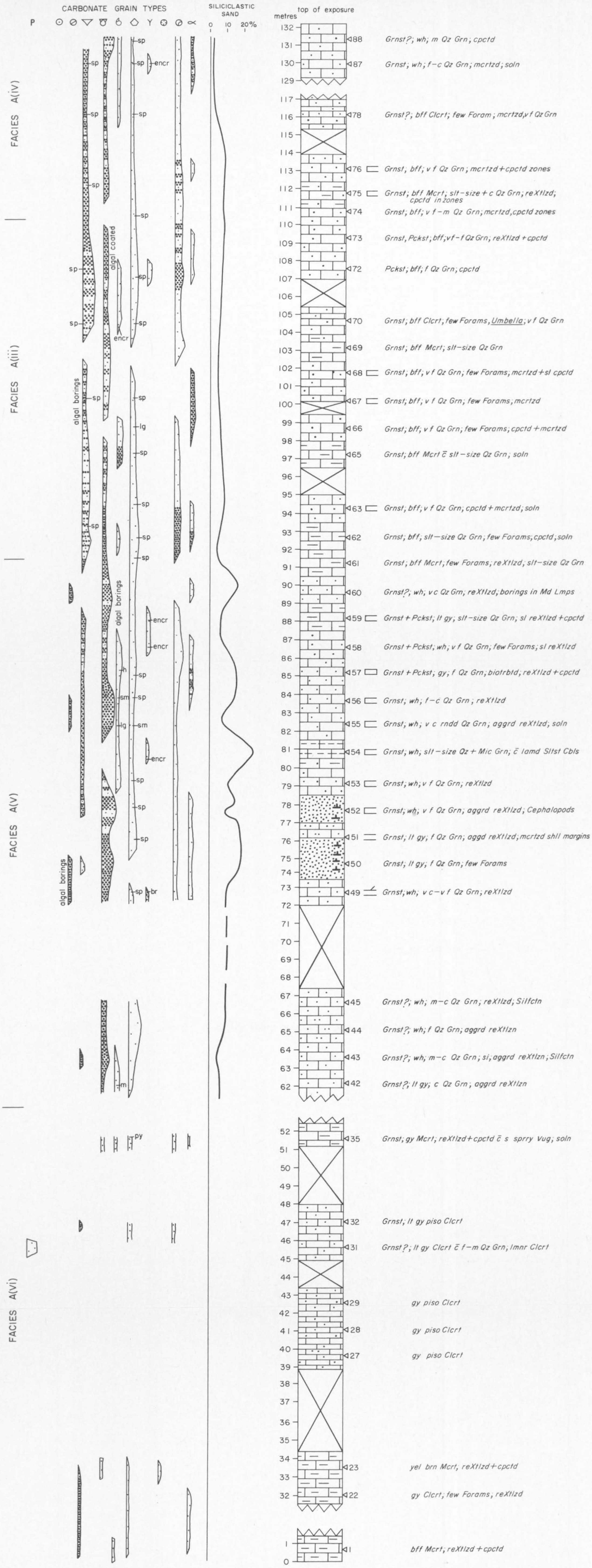

Figure 48. Type Section WCB 103, south of Twelve Mile Bore, Laurel Formation.

AUS 1 / 598