GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 134

GEOLOGY OF THE ONSHORE BONAPARTE AND ORD BASINS IN WESTERN AUSTRALIA

BY
A. J. MORY AND G. M. BEERE

DEPARTMENT OF MINES
WESTERN AUSTRALIA

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Frontispiece *Landsat mosaic of the northern East Kimberley region with a superimposed outline of the Bonaparte and Ord Basins and the Halls Creek Fault. Reproduced by courtesy of the Department of Lands Administration, Western Australia.*

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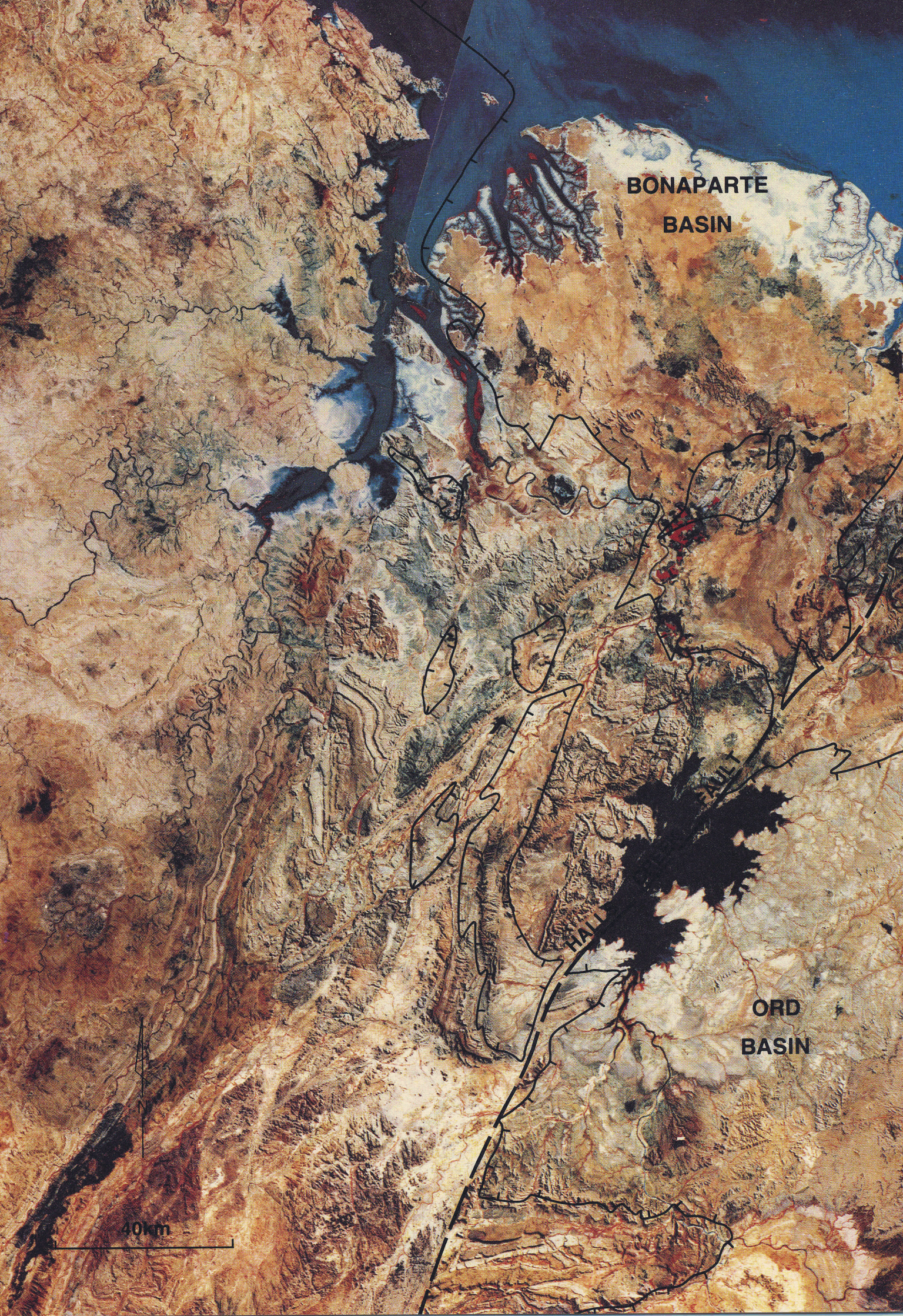
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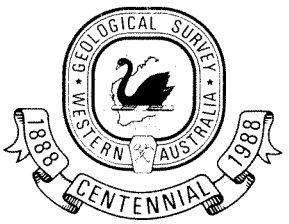

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SUMMARY

The onshore Bonaparte Basin and Ord Basin straddle the border of Western Australia and the Northern Territory in northwestern Australia. The basins are remnants of a much larger depositional province; Palaeozoic deposition in each basin was very similar, at least until the Frasnian, when the record in the Ord Basin ceases.

The north-northeast-oriented, onshore part of the Bonaparte Basin covers about 8000 km^2, in Western Australia, out of a total basin area of 270 000 km^2. This part of the basin lies west of, and parallel to, the Halls Creek Fault. It contains up to 6 km of folded and extensively faulted Cambrian to Permian sediments, with minor volcanics. Along the southern margin of the basin the Carlton and Burt Range Shelves are separated by the Precambrian Pincombe Inlier. To the north the shelves deepen into the northwest-trending Petrel Sub-basin which comprises most of the Bonaparte Basin and extends offshore. To the south, three half-grabens, the Ragged Range, Dillon Spring, and Mount Rob–Gap Point Outliers, are eroded remnants of a large graben parallel to the Halls Creek Fault.

The Ord Basin lies to the east of the Halls Creek Fault and south of the Bonaparte Basin. This basin covers a total area of 40 000 km^2, of which about 16 000 km^2 lies in Western Australia. It contains three gently folded asymmetrical synclines: the Hardman, Rosewood, and Argyle Synclines. The basin contains up to 2.5 km of Cambrian and Devonian sediments, with extensive basal volcanics. Minor Cainozoic sediments have a patchy distribution.

In the Palaeozoic, three phases of basin evolution are recognized.

(a) *Cambrian to Ordovician:* Within this phase there were two stages of intracratonic deposition. An initial stage of Early Cambrian subaerial volcanics (Antrim Plateau Volcanics) occurred over a large area of Northern Australia. They are thickest in the Ord Basin (1100 m) suggesting that this region was the major eruptive centre. This stage was followed by Middle Cambrian to Ordovician shallow-marine and marginal-marine clastics and carbonates (Goose Hole and Carlton Groups). These are up to 1200 m thick and conformably overlie the volcanics.

(b) *Late Devonian to Late Carboniferous:* Within this phase three stages of sedimentation, associated with northwest-oriented rifting in the Petrel Sub-basin, took place. Initially, Frasnian continental and shallow-marine clastic deposition (Cockatoo and Mahony Groups) accompanied two major periods of tensional faulting associated with the north-northeast-oriented Halls Creek Fault. This sequence, which unconformably overlies gently tilted Cambrian rocks, is up to 2700 m thick in the Ragged Range Outlier and thins to the north and south. In the second stage, Famennian to Middle Tournaisian carbonates and clastics (Ningbing and Langfield Groups) were deposited in reefal and shallow-marine environments on the shelves. At the same time, fine clastics (Bonaparte Formation) were deposited in basinal environments in the Petrel Sub-basin. Although the aggregate thickness of this sequence is more than 2000 m on the shelves, local faulting and erosion, due to late Tournaisian uplift along the basin margins, have reduced this to 1100 m maximum in any one section. During the third stage, Visean to Westphalian clastics and minor carbonates (Weaber Group) were deposited in offshore to fluvial environments as a deltaic basin-fill sequence on both shelves and in the Petrel Sub-basin. The sequence is unconformable on faulted and folded older sediments. It ranges from 600 m thick on the shelves to 2400 m thick in the Petrel Sub-basin.

(c) *Latest Carboniferous to Early Permian:* Following broad folding of Carboniferous sediments, there was glacial, continental, and shallow-marine clastic deposition (Keep Inlet Formation). This occurred partly in response to movements on the Cockatoo Fault and may represent sedimentation in a northeasterly trending graben. The onshore sequence is up to 480 m thick, but offshore the section ranges from 670 m to 1600 m.

The Palaeozoic sequence is unconformably overlain by Cainozoic alluvium, sand plains, soil, and coastal deposits. In the Ord Basin, a thin fossiliferous Miocene limestone is also present.

The Bonaparte Basin has moderate potential for economic hydrocarbon accumulations, unlike the overmature Ord Basin. Two significant gas flows and numerous bitumen shows are recorded from the onshore Bonaparte Basin.

Since the discovery of a carbonate-hosted, silver-lead-zinc deposit at Sorby Hills, there have been numerous exploration programs for base metals in the Bonaparte Basin. However, no further discoveries of economic significance have been made.

The Argyle kimberlite pipe (AK1) intrudes Proterozoic sediments immediately south of the Ragged Range Outlier. Diamonds derived from the pipe are found in Cainozoic gravels in nearby parts of the Bonaparte and Ord Basins.

CHAPTER 1

Introduction

LOCATION AND BASIN DEFINITIONS

The Bonaparte and Ord Basins are located in northwest Australia, straddling the border between Western Australia and the Northern Territory (Fig. 1).

The Bonaparte Basin lies on the northwestern side of the Halls Creek Fault and extends offshore, to the north, to cover an area of approximately 270 000 km^2, of which approximately 8 000 km^2 lies onshore in Western Australia. The "Bonaparte Gulf Basin" was named by Reeves (1949) in an unpublished company report and was later modified to Bonaparte Basin by Laws (1981). Matheson and Teichert (1948) published a report covering the southern half of the basin which they named the "Burt Range Basin"; this name has since been used as one of the subdivisions of the Bonaparte Basin (Burt Range Shelf, this bulletin). The northern part of the onshore Bonaparte Basin was called the "Gulf Basin" by Maitland and Montgomery (1924, p. 86) although the name has been little used and is best abandoned.

The Ord Basin lies directly south of the Bonaparte Basin (east of the Halls Creek Fault) and covers an area of 40 000 km^2, of which 16 000 km^2 lies in Western Australia. The original definition of the "Ord River Basin" by Wade (1924), for the area "surrounded and underlain by basalt" on Ord River Station, is equivalent to the sedimentary sequence in the "Hardman Basin" (Hardman Syncline, this bulletin) of Matheson and Teichert (1948). This definition was modified, along with the name, by McWhae and others (1958) to include the basalt sequence and the "Rosewood and Argyle Basins" (Rosewood and Argyle Synclines, this bulletin) of Matheson and Teichert (1948).

SETTLEMENT, CLIMATE, AND VEGETATION

The Bonaparte and Ord Basins are largely covered by pastoral leases which were first taken up in the late 19th century. All are cattle stations, varying in size between 1000 and 4000 km^2. Areas not covered by pastoral leases are: the tidal flats north of Brolga Springs and Wyndham; the Ord River Irrigation Area around Kununurra; the catchment area surrounding Lake Argyle; and the Department of Agriculture regeneration areas which cover most of Ord River and Fox River Stations. In addition the following areas have been gazetted as quarantine areas for Noogoora Burr: along the Ord River between Buttons Gap and Mount Connection; the Nicholson River between Nicholson homestead and Marella Hole; and all of Gordon Downs Station. The Bungle Bungle Range in the Hardman Syncline is being considered as a

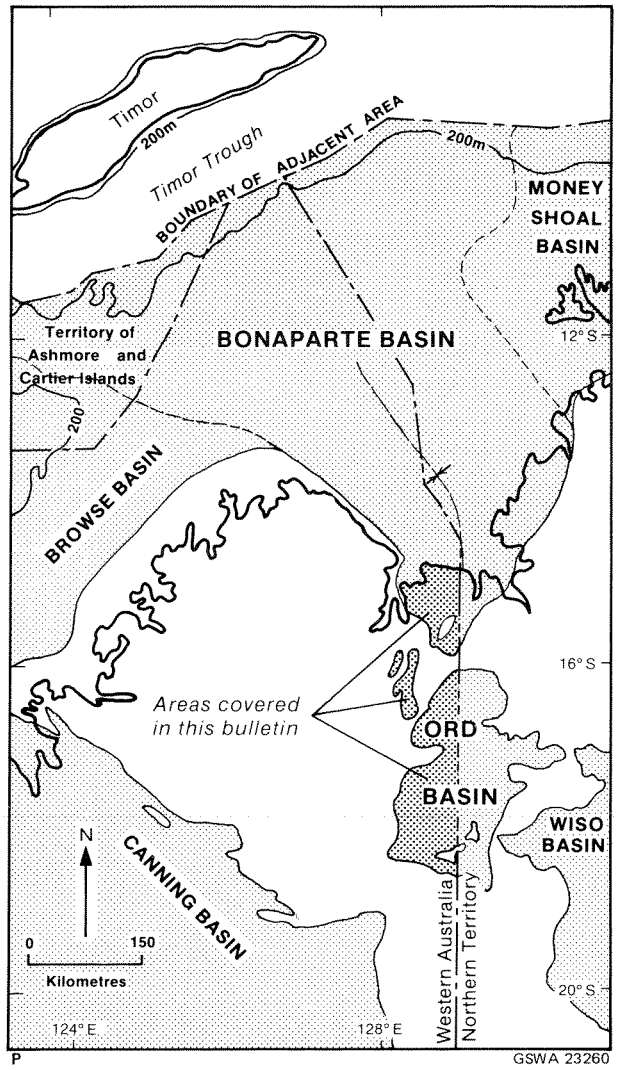

Figure 1. Location map showing the Bonaparte, Ord and surrounding Phanerozoic basins (in light stipple).

national park. Four small towns are situated in the East Kimberley area: Kununurra is the largest town with a population of 2081, followed by Wyndham (1509), Halls Creek (966), and Turkey Creek (212), (1981 census, Bartlett, 1983). The only bitumen roads in the region (in 1986) link these settlements: the Great Northern Highway north of Halls Creek; the section of the Duncan Highway which connects with the Victoria Highway in the Northern Territory; and the access road to Lake Argyle. A network of tracks of varying quality provides access on the pastoral leases. There is also a Royal Flying Doctor Service base in Wyndham.

The climate is subtropical with an average rainfall of 760 mm at Wyndham and 510 mm at Halls Creek. The rainy season is from December to April. In the north, it is warm to hot with average daily maximum temperatures ranging from 27°C to 36°C in January and 19°C to 30°C in July. In the south of the area, average daily maximum temperatures show a somewhat larger variation from 24°C to 37°C in January and 12°C to 27°C in July (Bartlett, 1983).

The vegetation of the East Kimberley area has been described by Beard (1979). Most of the Bonaparte Basin is covered by moderately dense high-grass savanna woodland, with hummock grass and spinifex on rocky hills. In the Ord Basin the vegetation is primarily controlled by lithology. Short-grass low-tree savanna, with tree steppe on stony rises, covers most of the basalt areas and plains developed over sandstone. Hard spinifex, with few trees, covers limestone outcrop. Virtually treeless short-grass savanna covers shaly areas, and sparse tree steppe with spinifex occurs on sandstone hills.

PHYSIOGRAPHY

The physiography of the Kimberley region was first described by Jutson in 1914 and later revised by him in 1934. The East Kimberley region was specifically dealt with by Paterson (*in* Stewart, 1970) who recognized the Kimberley Plateau, Sturt Plateau, and Ord-Victoria Regions; with the latter divided into the Cambridge Gulf Lowlands, Ord River Basin, and Halls Creek Ridges. A more recent treatment based on unpublished work by Plumb (Plumb and Gemuts, 1976) is summarized in Figure 2. A different approach to the physiography of the area was presented by Hays (1967) who recognized four Mesozoic-Cainozoic land surfaces (Fig. 121), in order of increasing age and height above sea level: Koolpinyah; Wave Hill; Tennant Creek; and Ashburton Surfaces. The following discussion is limited to units occurring within the Bonaparte and Ord Basins.

The Cambridge Gulf Lowlands comprise erosional, alluvial, tidal, and residual plains adjacent to Joseph Bonaparte Gulf. The unit is developed largely on Palaeozoic sediments of the Bonaparte Basin and includes numerous residual hills, but otherwise it rarely exceeds 100 m in elevation. Outliers of the Bonaparte Basin, apart from the Ragged Range Outlier, are included within the Cambridge Gulf Lowlands. The Ragged Range Outlier lies within the Kimberley Foreland.

In the Cambridge Gulf Lowlands the Koolpinyah Surface (Hays, 1967) developed in the coastal strip, as a response to Late Miocene–Early Pliocene uplift and subsequent erosion (Plumb and Gemuts, 1976). Since only small isolated remnants of older surfaces are preserved in the Cambridge Gulf Lowlands, the age of this physiographic unit is post-Koolpinyah Surface, *i.e.* Pliocene to Holocene.

The Ord Plains consist of alluvial and residual plains along the middle reaches of the Ord River, surrounded by plateaus, mesas and cuestas with structural benches cut into Cambrian volcanics. The Ord Plains cover a relatively low-lying area, drained by the Ord River and its tributaries, and approximately coincides with the Ord Basin north of Nicholson Station. Within the Ord Plains, remnants of the Wave Hill Surface are preserved where the Miocene White Mountain Formation is present (Hays, 1967). The top of the Bungle Bungle Range, at 500 to 600 m ASL, may represent a remnant of the Ashburton Surface of pre-Late Cretaceous age (Hays, 1967) or pre-Jurassic age (Plumb and Gemuts, 1976). The formation of tower karst in sandstone of the Bungle Bungle Range post-dates this surface and is discussed in Young (1986a; 1986b).

The immature drainage which is present in the area underlain by Cambrian volcanics, at the edge of the Ord Plains, suggests that it has developed relatively recently, probably in Pliocene to Holocene times.

The Sturt Plateau is a vast undulating Tertiary surface south of Nicholson Station. Outliers of this surface are present to the north in the Victoria River Region (Fig. 2). The Sturt Plateau is approximately equivalent to the Tennant Creek Surface of Hays (1967) in the East Kimberley–Victoria River region. Both Hays (1967) and Plumb and Gemuts (1976) assign a Late Cretaceous to Early Tertiary age to this surface.

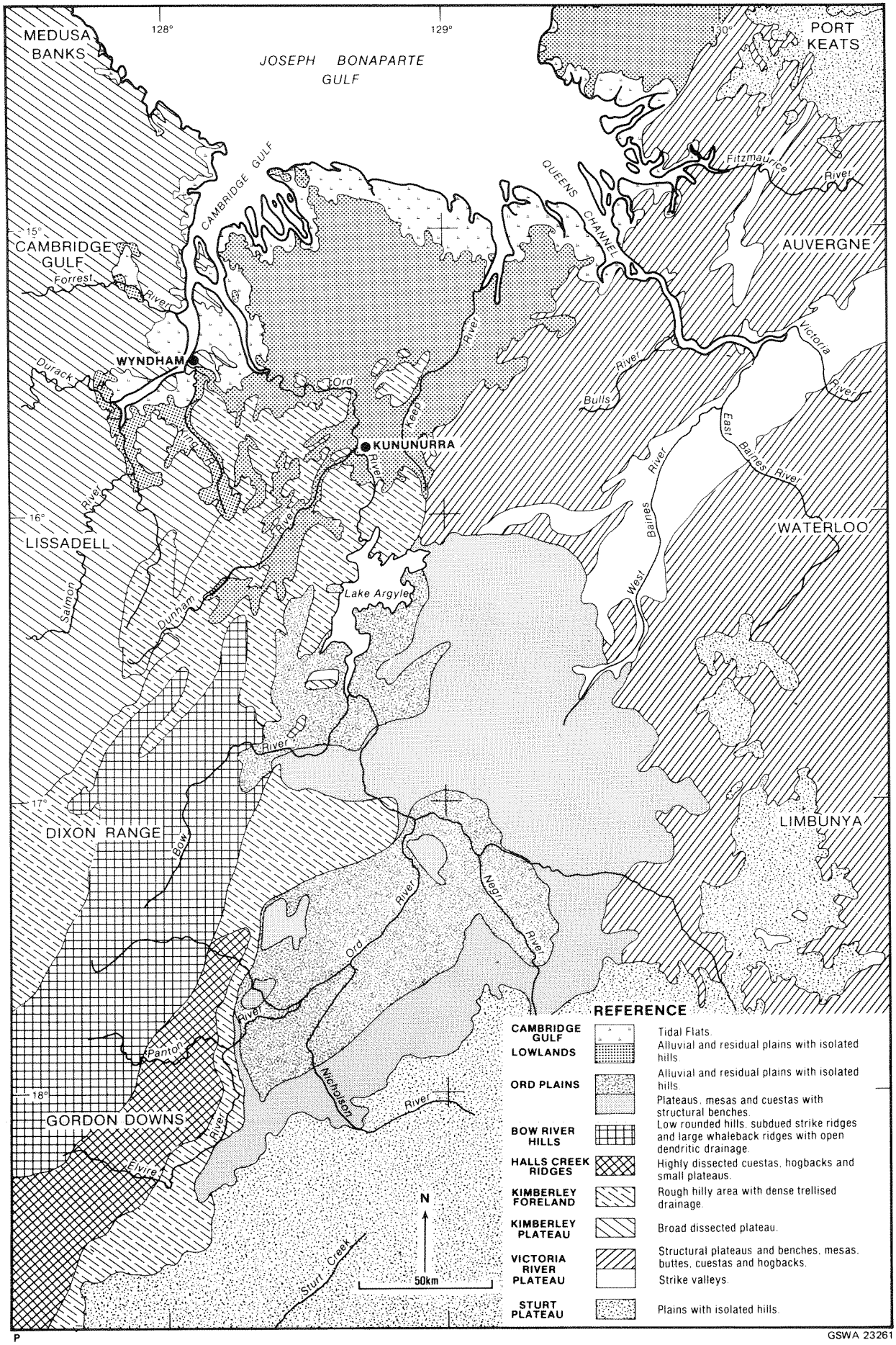

Figure 2. Physiographic sketch map compiled from 1:250 000 geological series explanatory notes.

PRESENT INVESTIGATION

The present study of the onshore Bonaparte and Ord Basins was carried out between 1980 and 1985, with fieldwork during the winter months of 1980 to 1982. As a result of this work, reviews have been published on the stratigraphy of the Ord Basin (Mory and Beere, 1985) and changes to the stratigraphy of the Bonaparte Basin (Beere and Mory, 1986). In this bulletin, G. M. Beere wrote Chapters 3, 5, 6, and 7, while A. J. Mory wrote Chapters 1, 2, 4, and 8; both authors wrote Chapters 9 and 10. Due to the repetition of facies in different formations within the Frasnian, Carboniferous, and Permian sequences, a facies analysis (encompassing entire groups) is presented in each of the chapters dealing with those sequences. A different approach was necessary for the chapters dealing with the Cambrian and Ordovician, and Famennian since (in those sequences) there is little repetition of facies between formations.

Symbols and facies codes used in measured sections throughout this bulletin are shown in Table 1 and Figure 3. The facies code is modified from a scheme developed for fluvial deposits (Miall, 1978) to apply to both continental and marine deposits.

PREVIOUS INVESTIGATIONS

The first geological investigation in the East Kimberley area was by Hardman (1885) who made observations over most of the Ord Basin. Subsequent surveys by Jack (1906) and Mahony (1922) in the Ord Basin drew substantially from Hardman's work. In their joint traverse across the Kimberley Region in 1923, Wade and Blatchford gave brief accounts of the Ord Basin (Wade, 1924; Blatchford, 1927). The first stratigraphic study of consequence was that of Matheson and Teichert (1948) who mapped the southern half of the Bonaparte Basin as well as the Ord Basin. Matheson and Teichert's work was further extended by Traves (1955) who is responsible for much of the stratigraphic nomenclature in the two basins.

The Bureau of Mineral Resources (BMR) carried out systematic mapping of the Bonaparte and Ord Basins from 1962 to 1965. This resulted in a number of publications on the Bonaparte Basin (listed in Roberts and Veevers, 1973) of which Veevers and Roberts (1968) and Kaulback and Veevers (1969) dealt with the Upper Devonian to Lower Permian and Cambro-Ordovician stratigraphy, respectively. The BMR mapping in the Northern Territory part of the Ord Basin was undertaken in 1969 and 1970, as part of a study of the Victoria River region, (Sweet and others, 1974). Results from the BMR mapping of the Western Australian portion of the Ord Basin are so far either unpublished reports (Dow and others, 1964; Dow, 1980) or published maps (Dow and Gemuts, 1967; Plumb, 1968; Gemuts and Smith, 1968).

TABLE 1. CODES FOR CLASTIC LITHOFACIES AND INTERPRETATIONS

Texture	*Code*	*Structure*	*Interpreted bedforms and processes*
Gravel	*Gm*	Massive (matrix supported)	Debris-flow deposits
	Gm	Massive (clast supported)	Longitudinal bars, lag deposits, sieve deposits
	Ga	Parallel beds	
	Gt	Trough cross-beds	Channel fills, sinuous dunes
	Gp	Planar cross-beds	Linguoid bars, transverse bars, straight-crested dunes
Sand	*Sm*	Massive	Rapid deposition, homogenization by deformation or bioturbation
	St	Trough cross-beds	Sinuous dunes (lower flow regime)
	Sp	Planar cross-beds	Linguoid bars, transverse dunes, straight-crested dunes (lower flow regime)
	Sh	Parallel lamination (parting lineation)	Plane beds (lower and upper flow regime)
	Sa	Parallel beds	
	Sl	Low-angle cross-beds (<10°)	Scour fills, antidunes, undulating beds (lower and upper flow regimes)
	Sr	Ripples (all types)	Ripples (lower flow regime and oscillation)
Silt/Clay	*Fr*	Ripples	Ripples (lower flow regime)
	Fh	Lamination	Planar to undulating beds, slow suspension deposition
	Fm	Massive	Massive beds, rapid suspension deposition, homogenization by bioturbation

Some facies represent several types of bed form which may be formed by different depositional processes (Miall, 1978, p.12; Harms and others, 1982; Collinson and Thompson, 1982). Consequently the interpreted bed forms and processes in this table are meant only as a guide.

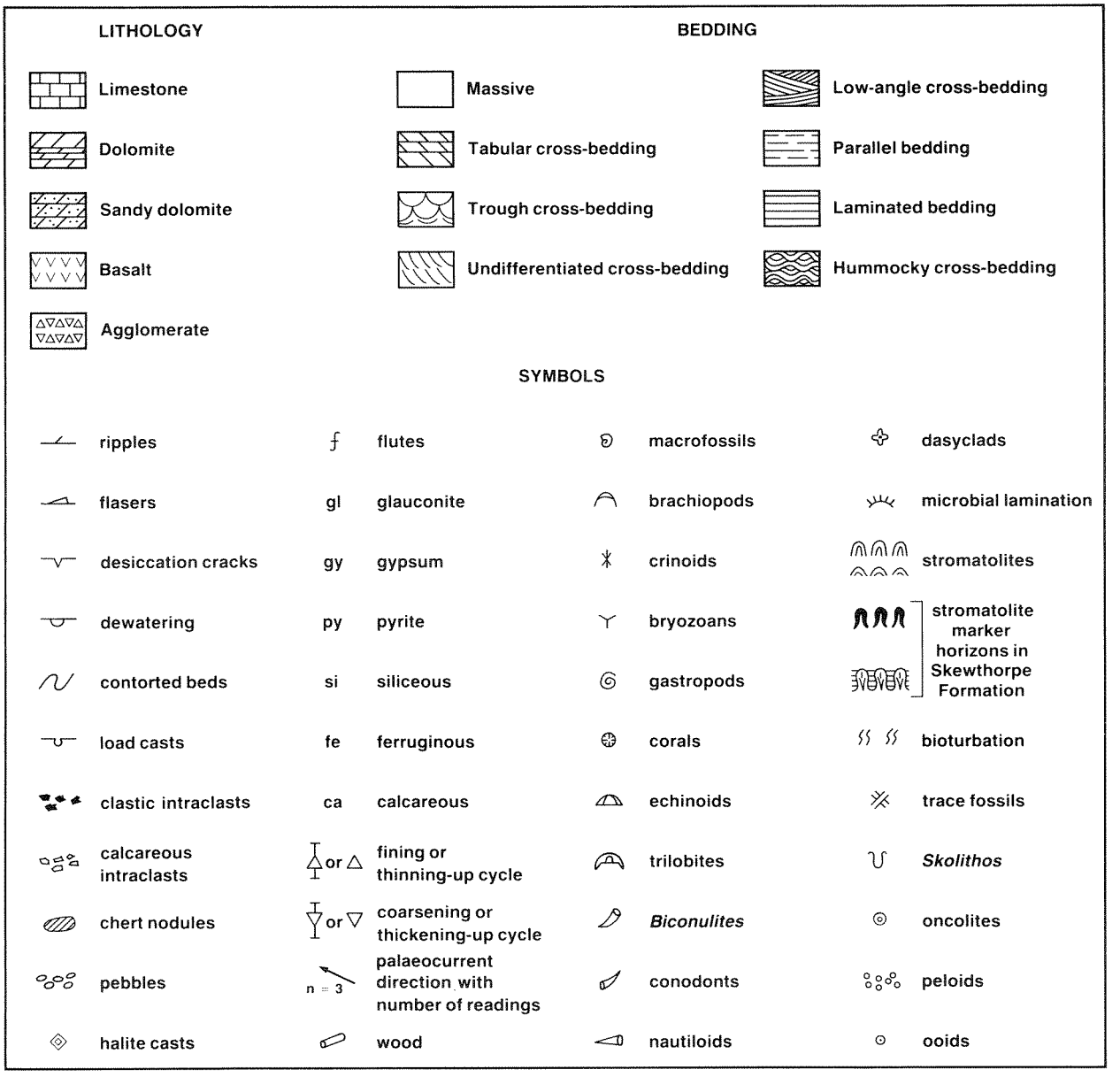

Figure 3. Symbols used in measured sections.

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Detailed mapping of the Palaeozoic sequence in Keep River National Park, by the Northern Territory Geological Survey in 1981 (Whitehead and Fahey, 1985), differs little from Veevers and Roberts' (1968) interpretation.

Petroleum and base-metal exploration has taken place in the Bonaparte Basin since the mid 1960s, mainly by one company — Australian Aquitaine Minerals (now Triako Resources Limited) and Elf Aquitaine Australia Petroleum. This company drilled 7 of the 11 onshore petroleum-exploration wells and discovered the Sorby Hills lead-zinc-silver prospect. By comparison, exploration in the Ord Basin has been relatively minor with intermittent mineral exploration chiefly for copper (in the Antrim Plateau Volcanics and Headleys Limestone) and the drilling of one petroleum-exploration well, Okes-Durack 1, in 1923–24.

Diamond exploration during the late 1970s over the East Kimberley region, included parts of the Bonaparte and Ord Basins. This culminated in the discovery of the Argyle Pipe in October 1979 by the Ashton Joint Venture.

Reviews of the Bonaparte and Ord Basins have been written by McWhae and others (1958), Guillaume (1966), Brady and others (1966), Playford and others (1975), Laws and Brown (1976), and Jones (1976).

TECTONIC SETTING

Both the Bonaparte and Ord Basins are defined as stratigraphic and structural elements in the manner outlined by Playford and others (1975, p. 224). The main belt of Phanerozoic outcrop in the Bonaparte Basin forms a broad downwarp

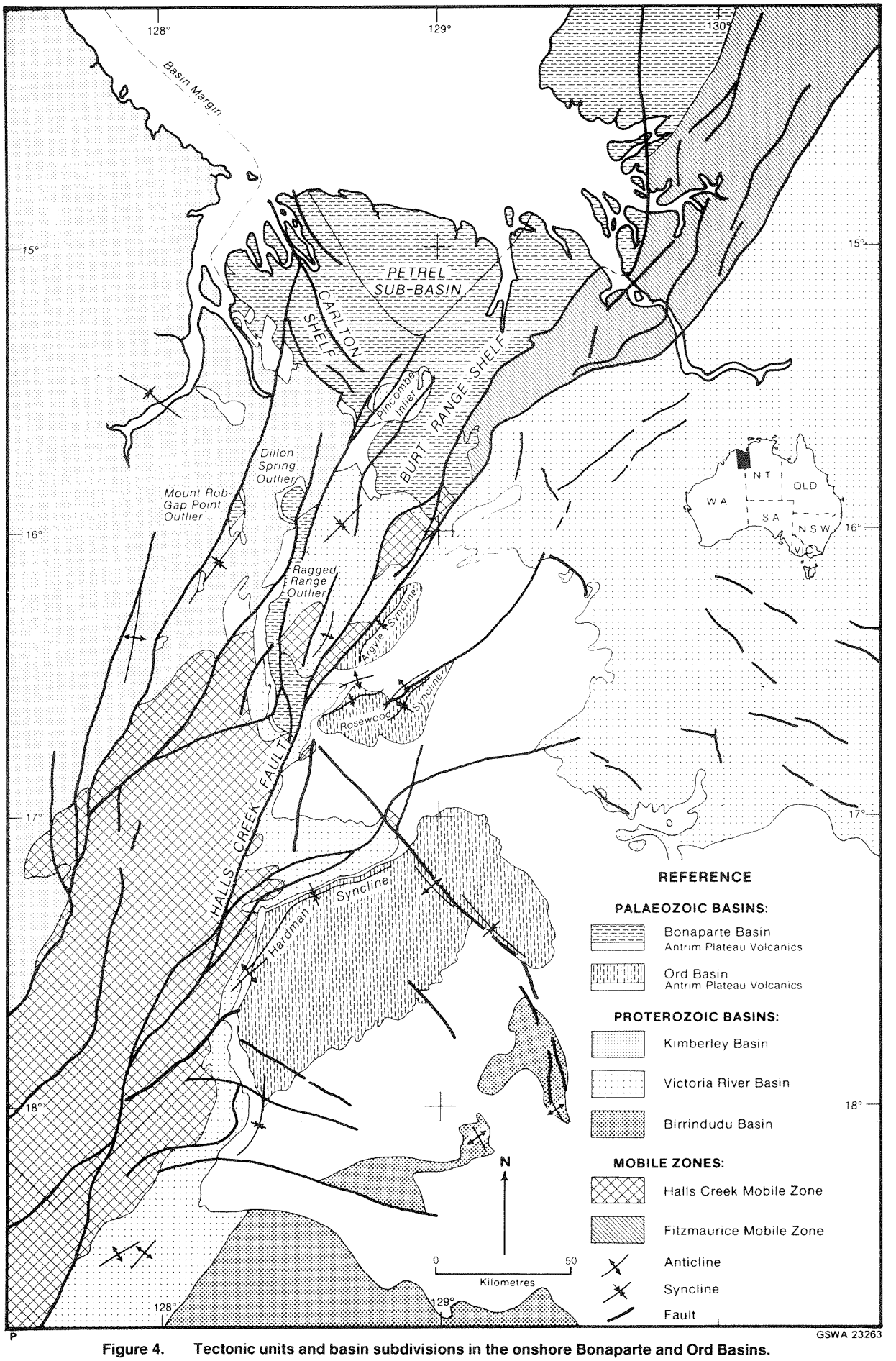

Figure 4. Tectonic units and basin subdivisions in the onshore Bonaparte and Ord Basins.

which plunges to the north (Fig. 1). Four subdivisions of the basin are recognized: Carlton Shelf, Burt Range Shelf, the southernmost part of the largely offshore Petrel Sub-basin, and the outliers (Fig. 4). The three outliers which lie in the Proterozoic Halls Creek Mobile Zone and Kimberley Basin are the Mount Rob–Gap Point, Dillon Spring, and Ragged Range Outliers (Fig. 4).

The lithostratigraphy developed in the four subdivisions of the basin is summarized in Figure 5.

The Ord Basin is an intracratonic basin of Phanerozoic age which overlies the Proterozoic Victoria River and Birrindudu Basins. The post-volcanic sequence is preserved in three synclinal areas, the Hardman, Rosewood and Argyle Synclines (Fig. 3) which cover an area of approximately 8 000 km^2. The stratigraphic succession in the three synclines is almost identical, with the most complete sequence being preserved in the Hardman Syncline. In the centre of the Hardman Syncline there is a circular feature 6 km in diameter, known as the Piccaninny Structure. This is of probable meteorite-impact origin and occurs in Devonian sandstone (Beere, 1983).

SEDIMENTARY SEQUENCE

The Palaeozoic sequence in the onshore Bonaparte and Ord Basins is summarized in Figure 5. Apart from lacustrine carbonates and unnamed superficial units of Cainozoic age, younger sediments are not present in the area discussed in this bulletin.

At the base of the succession, in the Bonaparte and Ord Basins, are continental tholeiitic basalts of Early Cambrian age. These basalts extend into the Northern Territory in the Daly River, Wiso and Georgina Basins. In both the Bonaparte and Ord Basins, intertidal to shallow-marine clastics with minor carbonate of Middle Cambrian age overlie the basalt. Marine sands continued to be deposited in the Bonaparte Basin until the Early Ordovician, whereas in the Ord Basin only fluvial sandstone of probable early Late Cambrian age is preserved. In both basins a break in the sequence is present, and sedimentation recommenced in the Late Devonian with alluvial fans forming along fault scarps which supplied coarse clastic sediment to fluvial, eolian, and shallow-marine environments. In the Ord Basin these Frasnian clastics are the youngest Palaeozoic sediments preserved. The sedimentary record continues into the Permian in the onshore Bonaparte Basin. A carbonate-reef complex developed around the edge of the Bonaparte Basin in the Famennian and is overlain by shallow-shelf clastics and carbonate of Early Carboniferous age. In the Petrel Sub-basin, deposition of black shale continued uninterrupted from the Late Devonian to the Visean, although a break in sedimentation is evident at the end of the Tournaisian in the Carlton and Burt Range Shelves. In the Early Visean the basinal shale encroached over the shelves and was followed by a deltaic sequence, grading offshore into shelf carbonate of Middle Visean to Namurian age. Upper Carboniferous and lower Permian sediments unconformably overlie the older Bonaparte Basin sequence. They consist of conglomerates deposited by a fan delta, on the southeastern side of the basin, as well as fluvial and glaciogene marine clastics to the north.

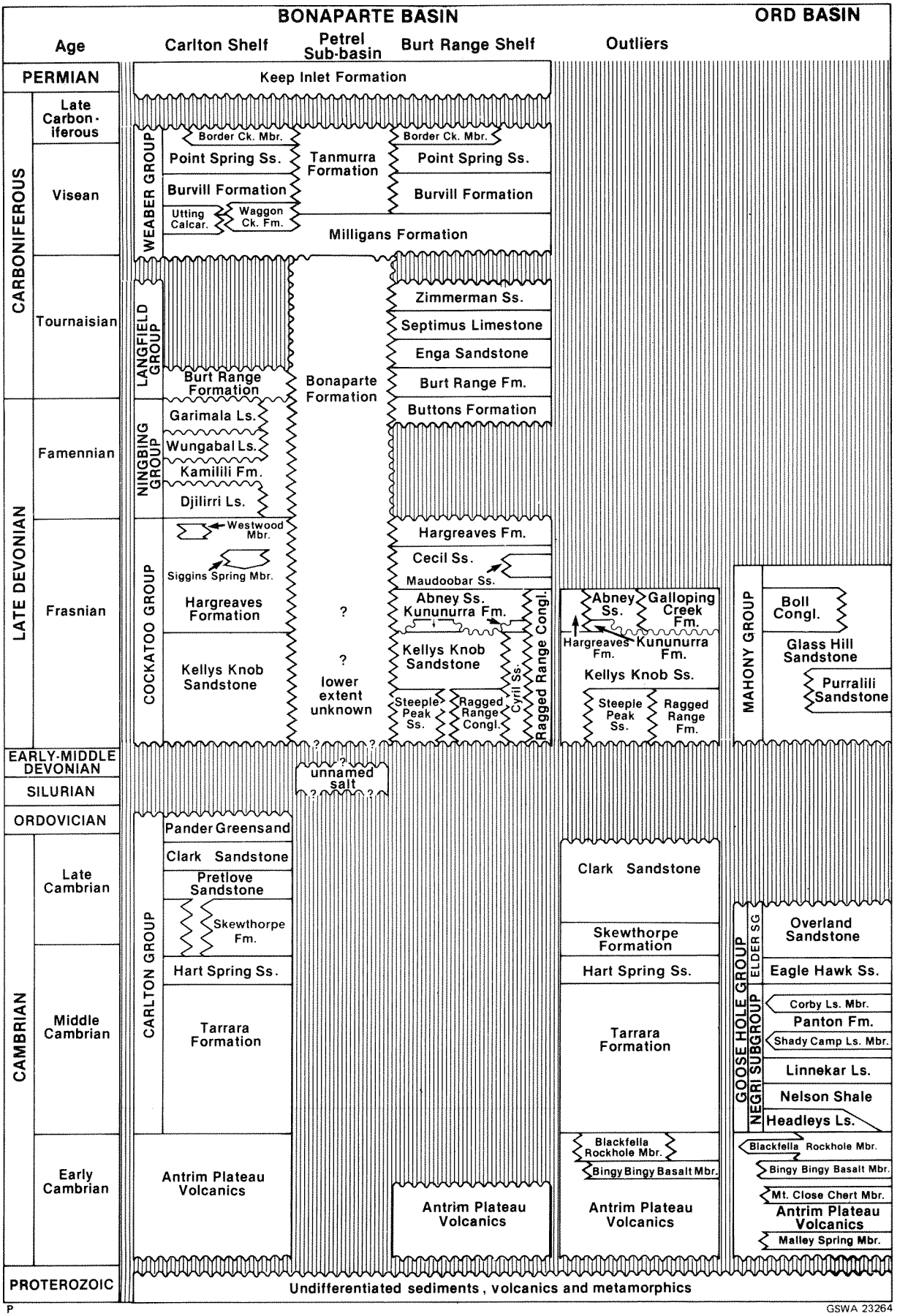

Figure 5. Summary of the Palaeozoic stratigraphy of the Bonaparte and Ord Basins.

CHAPTER 2

Cambrian and Ordovician of the Bonaparte and Ord Basins

INTRODUCTION

While the first geological investigation of the Cambrian sequence in the Ord basin was that of Hardman (1885), the Cambrian age was not established until Foord (1890) examined part of Hardman's collection. By comparison, Cambrian rocks in the Bonaparte Basin were not discovered until 1947 when Reeves collected fossils of that age from north of Carlton Hill (Reeves, 1949). The Cambrian sequence of both the Bonaparte and Ord Basins was first discussed in a single report by Traves (1955). Since then, the only papers to discuss the Cambrian of both basins were the general reviews in McWhae and others (1958), Playford and others (1975) and Leslie and others (1976).

At the base of the Cambrian section, in both basins, the sequence is dominated by tholeiitic basalts (Antrim Plateau Volcanics). The volcanics are succeeded by a dominantly clastic sequence which, in the Ord basin (Goose Hole Group), extends into the early Late Cambrian (Mindyallan). In the Bonaparte Basin the sequence (Carlton Group) continues into the Ordovician. In both basins the sequences are unconformably overlain by Devonian clastics.

In the Ord Basin the Cambrian sequence is exposed in three asymmetrical synclines (Fig. 6), whereas in the Bonaparte Basin the Cambrian sequence is restricted to a narrow northwest-striking belt. This belt dips to the northeast and the sequence within it is repeated up to four times by strike faults (Fig. 7). The stratigraphy of the Cambrian sequence of the Ord and Bonaparte Basins is summarized in Figures 8 and 9, respectively.

ANTRIM PLATEAU VOLCANICS

Definition: David (1932) was the first to name the Antrim Plateau Basalts, taking the name from the Great Antrim Plateau (Hardman, 1885).

Traves (1955) modified the name to Antrim Plateau Volcanics because the unit includes a number of lithologies. Although Traves did not designate a type section, all subsequent workers have considered the Great Antrim Plateau to be the type area. Playford and others (1975, p. 398) suggested that the section west of trigonometric station J37 (Hardman, 1885) "may be taken as the type section." This designation is presumably

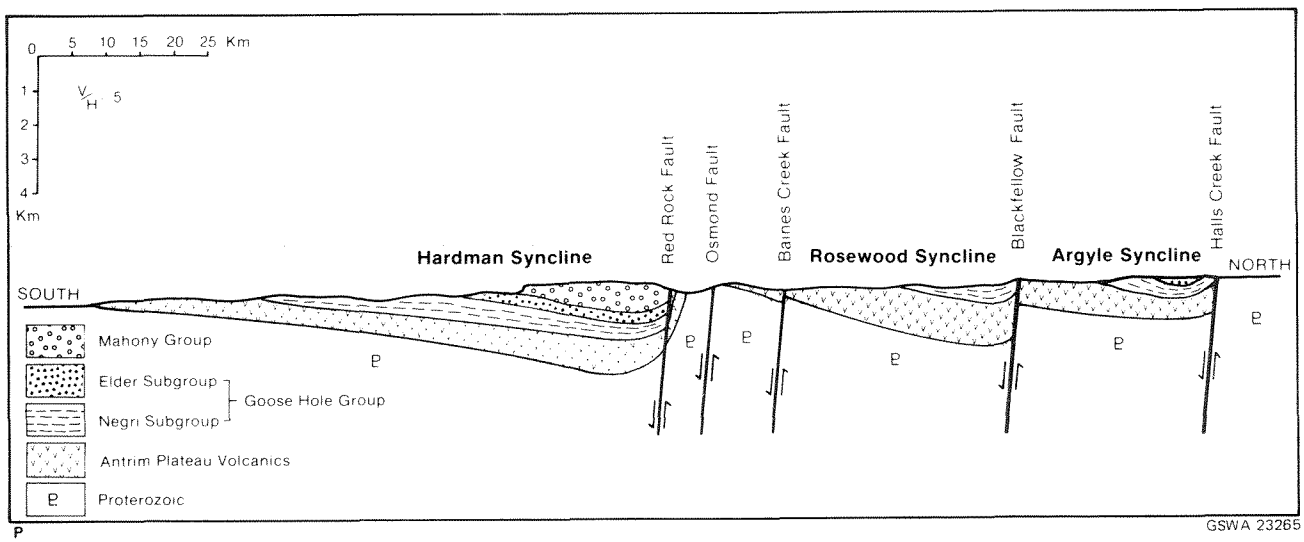

Figure 6. Schematic cross-section of the Ord Basin showing the asymmetrical nature of the Hardman, Rosewood, and Argyle Synclines.

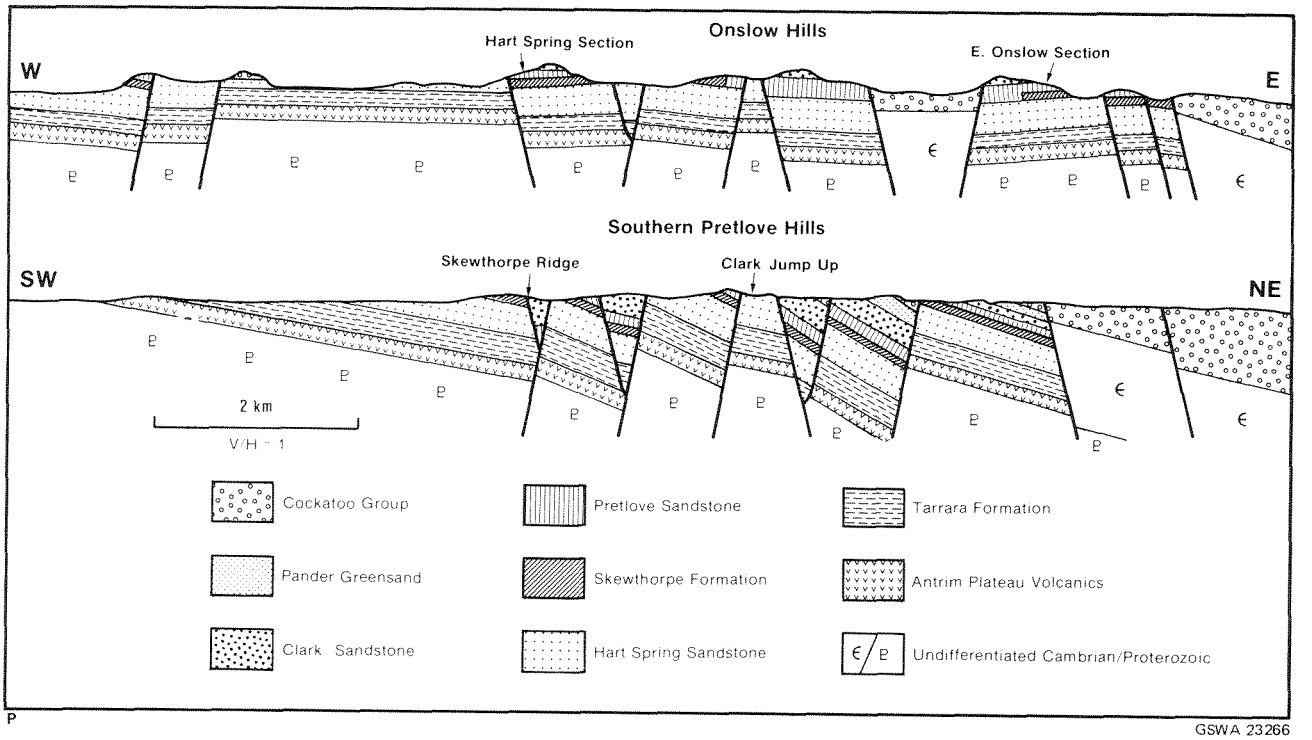

Figure 7. Cross-sections through the Carlton Group in the Bonaparte Basin, across Onslow Hills and the southern Pretlove Hills, showing multiple-fault repetition of the succession.

based on the two sections shown by Dow and Gemuts (1967) on DIXON RANGE* which Dow (1980, p. 3) later stated "had been shown, incorrectly, as type sections...". The only well exposed section in the Great Antrim Plateau, with both the upper and lower contacts visible, is an east-west transect through trigonometric station J32 (Hardman, 1885), 20 km south of Turner outstation. However, ground access to that section is only via Fox River and is difficult.

Consequently, Mory and Beere (1985) designated the type section in the Spring Creek area where the diverse lithologies, which make up this unit, are better shown. Also, access via the Duncan Highway is much easier than at J32. The type section extends from the eastern end of Moonlight Valley at 17°02'20"S, 128°44'25"E (base), then 12 km north to the base of the Blackfella Rockhole Member at 16°36'25"S, 128°45'50"E. From there the section extends 24 km along strike to the Camel Back Hills at 16°45'55"S, 128°54'00"E, finishing 2.5 km north-northwest at the base of the Headleys Limestone at 16°44'50"S, 128°53'30"E.

Four named members and one unnamed sandstone member are recognized in the Antrim Plateau Volcanics. In the Ord Basin these are (in ascending order): the Malley Spring Member; Mount Close Chert Member; Bingy Bingy Basalt Member; and Blackfella Rockhole Member. In the Bonaparte Basin an unnamed sandstone member is recognized at the base of the Antrim Plateau Volcanics near Eclipse Yard (Plate 1). The Bingy Bingy Basalt and the Blackfella Rockhole Members are both present in the Ragged Range Outlier of the Bonaparte Basin.

The Malley Spring Member (Mory and Beere, 1985) was named after Malley Spring near Texas Downs homestead. The member consists of siltstone and sandstone, which are exposed in Moonlight Valley approximately 50 m above the base of the Antrim Plateau Volcanics. The type section is at the eastern end of Moonlight Valley at 17°02'50"S, 128°43'05"E.

The Mount Close Chert Member (Mory and Beere, 1985) was named after Mount Close and consists of laminated chert with intraformational breccia and stromatolites. The type section is 2.5 km northeast of Mount Close, at the side of the Duncan Highway at 16°56'25"S, 128°51'30"E.

The Bingy Bingy Basalt Member was named by Sweet and others (1974, p. 100) for the glomeroporphyritic basalt which underlies the Blackfella Rockhole Member. The type section is 7 km northeast of Bingy Bingy Springs in the Northern Territory at 17°32'S, 129°15'E.

FOOTNOTE: *Names of 1:250 000 scale sheets are printed in capitals to avoid confusion with place names.

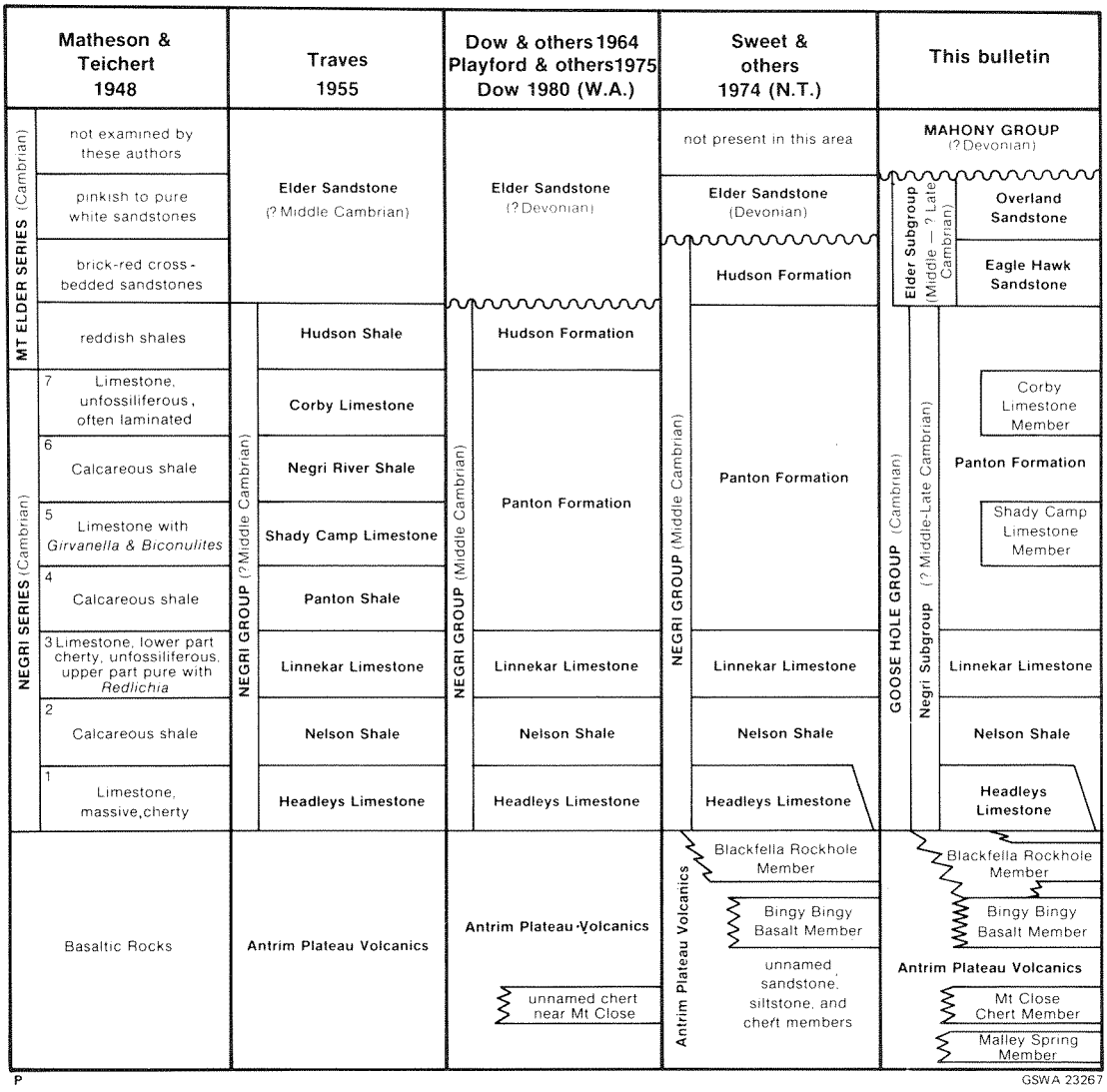

Figure 8. Stratigraphy of the Cambrian sequence in the Ord Basin showing the relationship with previous stratigraphic nomenclature. The correlation with the Cambrian of the Bonaparte Basin is shown in Figure 5.

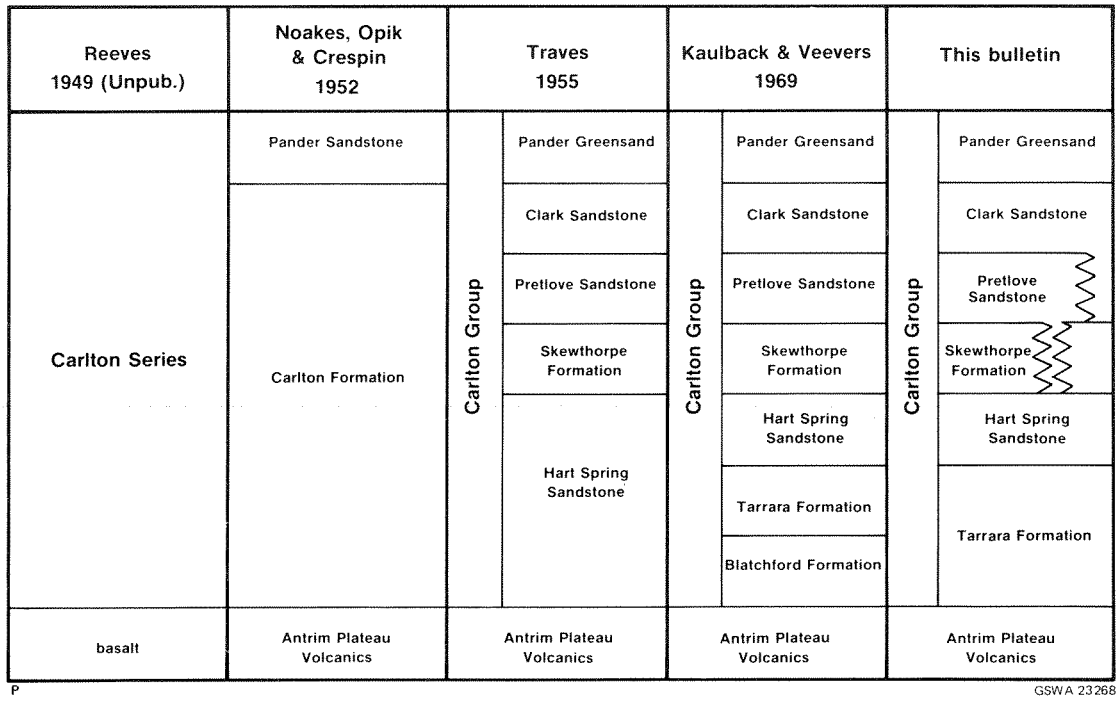

Figure 9. Stratigraphy of the Cambrian sequence in the Bonaparte Basin showing the relationship with previous stratigraphic nomenclature.

The Blackfella Rockhole Member was originally named by Sweet and others (1974, p. 99) for the "agglomerate, minor basic lavas, and thin lenses of sandstone and siltstone" at the top or the Antrim Plateau Volcanics in the Northern Territory. The abrupt upper contact and gradational lower contact of the agglomerate, with fine-grained basalt, suggest that the agglomerate represents the upper part of a single flow and that the fine-grained basalt and agglomerate should be included within one unit. Thus, while Sweet and others (1974) defined the base of this member at the lowest agglomerate horizon, Mory and Beere (1985) amended this definition to include the fine-grained basalt below the agglomerate. The type section of this member is at Blackfella Rockhole (17°23'S, 129°06'E) in the Northern Territory. Since the base of the Blackfella Rockhole Member is not exposed in the type section, Mory and Beere (1985) named the section east of Linnekar Creek near Charra Rockhole as a reference section.

Lithology: The Antrim Plateau Volcanics consist predominantly of massive, vesicular, amygdaloidal and porphyritic basalt, with minor agglomerate, siltstone, sandstone, tuff and chert. Distinctive horizons of glomeroporphyritic basalt, agglomerate or sediment have each been given formal status as members. Most basalt is fine to medium grained with highly vesicular or amygdaloidal flow tops. The lavas are tholeiitic, consisting of plagioclase, clinopyroxene and opaques, within a matrix of devitrified glass or a quartz-feldspar residuum (Bultitude, 1976). Vesicles are commonly filled with coarse quartz, chert, calcite, agate, chlorite, prehnite or pumpellyite. Within flows, vesicles generally do not have a pronounced elongation except for pipe vesicles at the bases of flows (Fig. 10).

Burial metamorphism just into the prehnite-pumpellyite facies indicates a temperature of burial of between 160 and 200° C (Ahmat, 1984). In terms of a "normal" geothermal gradient (30° C/km) this temperature suggests a depth of burial between 5 and 7 km for the Antrim Plateau Volcanics.

The Malley Spring Member consists of white and grey siltstone and medium- to coarse-grained bimodal sandstone. The type section at the eastern end of Moonlight Valley consists chiefly of siltstone; but sandstone becomes progressively more abundant to the west. West of Horse Creek Well the Malley Spring Member passes laterally into a medium- to coarse-grained sandstone, 4 to 5 m thick, at the base of the Antrim Plateau Volcanics. The sandstone is parallel laminated or very low-angle cross-bedded, similar to the thin tuffaceous sandstone at the base of the Antrim Plateau Volcanics at Tarrara Bar in the Bonaparte Basin. Near Eclipse Yard in the Bonaparte Basin a large-scale cross-bedded sandstone member (Fig. 11), wih foresets up to 5.5 m high, is present at the base of the Antrim Plateau Volcanics. The sandstones at the base of the unit at Tarrara Bar and Eclipse Yard may be equivalent to the Malley Spring Member.

The Mount Close Chert Member consists of laminated chert with common intraformational breccia and conical non-branching stromatolites up to 12 cm in diameter. Minor silicified siltstone is also present.

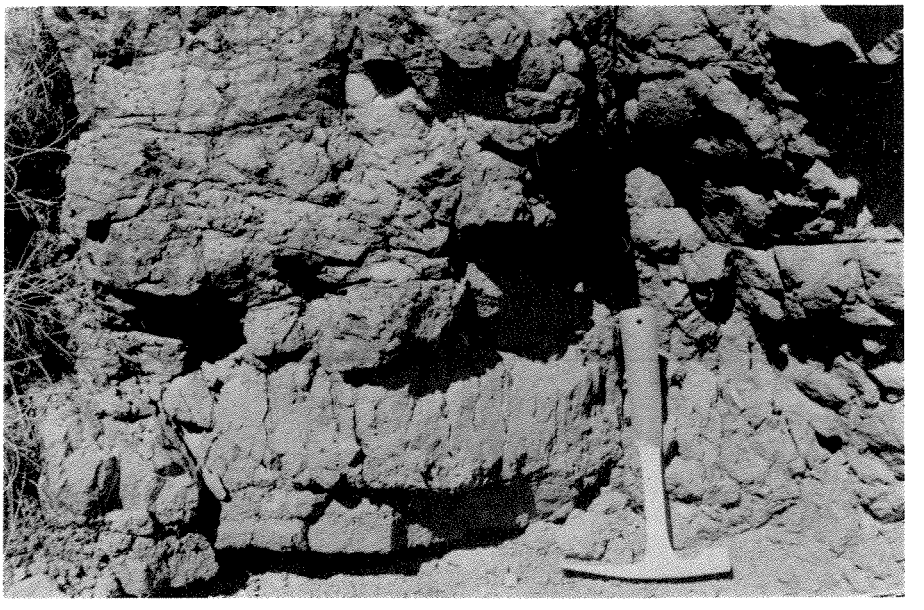

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Figure 10. Pipe vesicles at the base of a basalt flow in the Antrim Plateau Volcanics, Wild Dog Bore, Spring Creek Station.

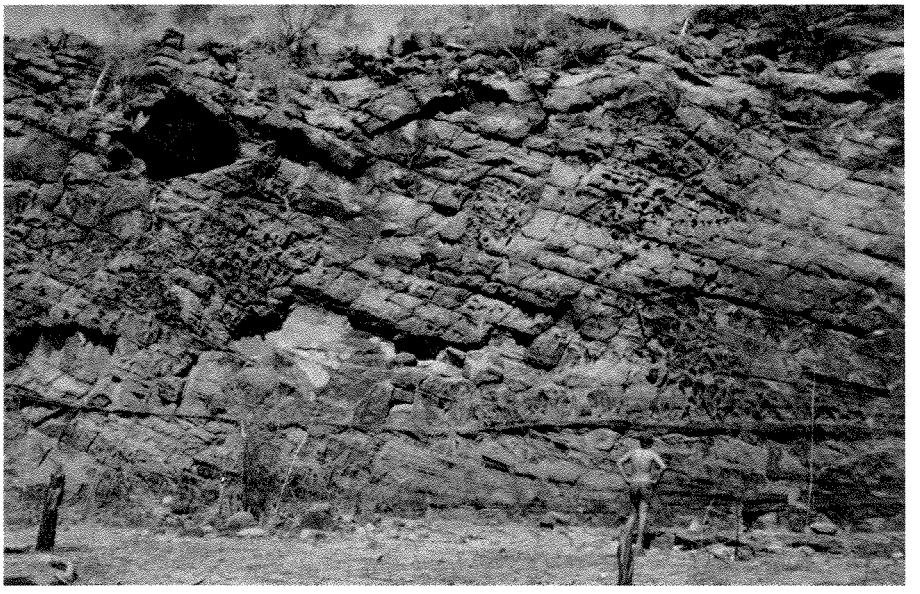

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Figure 11. Large-scale cross-beds of probable eolian origin at the base of the Antrim Plateau Volcanics, Eclipse Yard. The upper foresets are 5.5 m thick.

The Bingy Bingy Basalt Member consists of massive, fine- to medium-grained glomeroporphyritic basalt with clots of plagioclase crystals up to 1 cm in diameter. The groundmass consists predominatly of plagioclase crystals which form a meshing framework, enclosing pyroxene granules and minor iron-titanium oxides.

The Blackfella Rockhole Member consists of a number of lava flows composed of very fine-grained basalt with agglomerate at the top of the flows. The agglomerate forms breakaways at the tops of hills and is usually composed of a matrix-supported framework of angular clasts 5–20 cm in diameter, occasionally reaching 0.6 m in diameter. Clasts are largely of vesicular or amygdaloidal basalt with minor massive basalt, similar to that below the agglomerate. Near the base of the agglomerate horizons, clasts commonly show resorbed boundaries.

Interbedded with the basalt of the Antrim Plateau Volcanics are sandstone and siltstone. These are usually present between flows but may also fill voids in underlying agglomerates or fissures at the top of the underlying flow (Fig. 12). In the Northern Territory, Sweet and others (1974) mapped five lenticular clastic terrigenous units interbedded with the volcanics. The stratigraphic position of most of these units is difficult to determine due to low dips and poor outcrop.

Stratigraphic relationships: The Antrim Plateau Volcanics unconformably overlie Proterozoic sediments, locally with a marked angular relationship. The irregular nature of this unconformity suggests that the Antrim Plateau Volcanics filled palaeovalleys, eroded into the Proterozoic rocks. The best examples of such palaeovalleys are north of Doon Doon homestead.

The Antrim Plateau Volcanics are conformably overlain by the Headleys Limestone or Nelson Shale, at the base of the Negri Subgroup in the Ord Basin, and by the Tarrara Formation, at the base of the Carlton Group in the Carlton Shelf of the Bonaparte Basin. In the Burt Range Shelf of the Bonaparte Basin, the Antrim Plateau Volcanics are unconformably overlain by clastics of the Devonian Cockatoo Group.

The upper contact is generally sharp but concordant. Ferruginization and silicification of the basalts at the top of the Antrim Plateau Volcanics are probably recent events, not necessarily the result of erosion or weathering prior to the deposition of the Negri Subgroup, as suggested by Sweet and others (1974) and Dow (1980).

Distribution and thickness: In Western Australia the Antrim Plateau Volcanics lie at the base of the Bonaparte and Ord Basin sequences, as well as outcropping as isolated outliers west of these basins. Of the outliers, those near Margaret River Station on MOUNT RAMSAY are the furthest to the west, at 126°45'E (Roberts and others, 1972). In the Northern Territory, extensive outcrops of the Antrim Plateau Volcanics are also present in the western Victoria River region where the unit lies at the base of the Daly River and Wiso Basin sequences. The Antrim Plateau Volcanics and their correlatives are exposed over an area of about 35 000 km^2 in the Northern Territory and extend over a further 115 000 km^2 in the Ord,

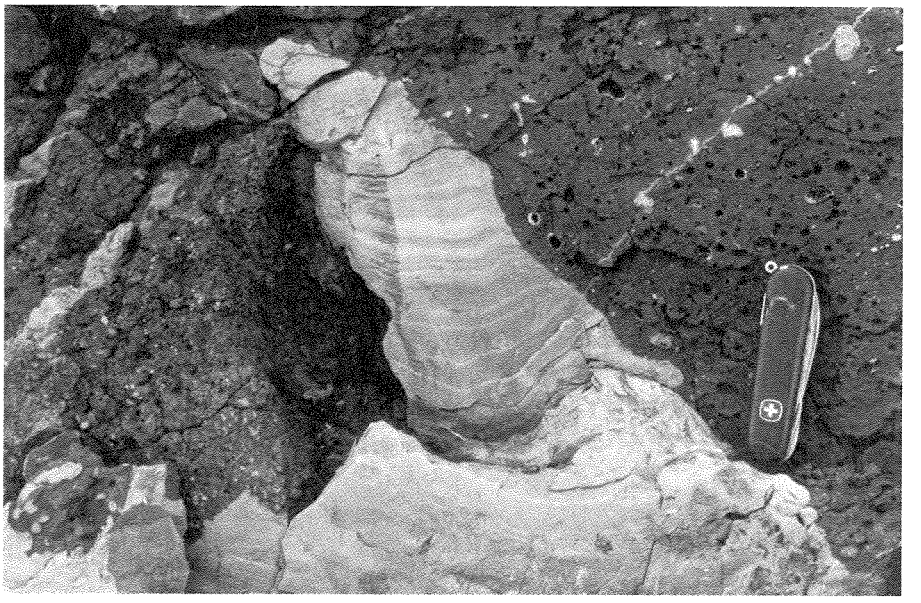

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Figure 12. Cross-section of a silt-filled fissure in vesicular basalt near a flow top in the Antrim Plateau Volcanics at Tarrara Bar.

Wiso and Daly River Basins. The lava field may originally have had an area of 300 000 to 400 000 km^2 (Bultitude, 1976). The greatest thicknesses of Antrim Plateau Volcanics are on the Western Australian side of the border where the unit varies in thickness from 1100 m (Negri-Ord River section) to 340 m (south of Turner outstation) in the Ord Basin. The type section near Spring Creek is approximately 1000 m thick. In the Bonaparte Basin the unit is much thinner (155 m at Tarrara Bar) or may be absent, as in some localities in the Burt Range Shelf (Fig. 13). To the east, in the Northern Territory, the unit thins to 237 m near Top Springs on VICTORIA RIVER DOWNS. The southernmost extent of the Antrim Plateau Volcanics is near Mongrel Downs on THE GRANITES, where it is about 50 m thick.

The Malley Spring Member is only present in Moonlight Valley, on Texas Downs Station, and varies in thickness from 3 to 5 m. The member may be equivalent to the Kinevans Sandstone (Sweet and others, 1974) on WATERLOO and the unnamed sandstone member at the base of the Antrim Plateau Volcanics in the Bonaparte Basin.

The Mount Close Chert Member is up to 5 m thick and, apart from the Spring Creek area, is also recognized west of J37 and (questionably) at Mount Wittenoom on GORDON DOWNS.

The unnamed laminated chert member mapped by Sweet and others (1974) in the southern Victoria River region is possibly a correlative of the Mount Close Chert Member.

The main belt of outcrop of the Bingy Bingy Basalt Member lies on the southeastern limb of the Hardman Syncline, in the Ord Basin between Agate Hills in Western Australia and the Negri River in the Northern Territory. The unit is also present as lenses near Spring Creek Station, south of Bungle Bungle outstation and in the Bonaparte Basin near Doon Doon Station. In the type section near Bingy Bingy Springs, the member is 40 m thick and reaches a maximum thickness of 130 m near Charra Rockhole, while at Spring Creek and Doon Doon Stations it is approximately 20 m thick.

The Blackfella Rockhole Member is widely distributed in the Ord Basin, being present virtually all the way round the Hardman and Rosewood Synclines and on the southern limb of the Argyle Syncline. In the Bonaparte Basin the member is only present east of Doon Doon. In the type section at Blackfella Rockhole the member is 71 m thick (base is not exposed). The member reaches a maximum thickness of 140 m at Charra Rockhole.

Individual flows within the Antrim Plateau Volcanics are often difficult to see. However, vesicle-rich horizons (which generally represent flow tops) usually weather out preferentially and form prominent benches on the sides of hills. The thicknesses of individual lava flows, given here, are the thicknesses measured between such benches. Lava flows usually range from 5 to 80 m, exceptionally reaching 114 m (Bultitude, 1976). The average flow thickness is between 25 and 35 m. At Tarrara Bar — the only well exposed section through this unit in the Bonaparte Basin —

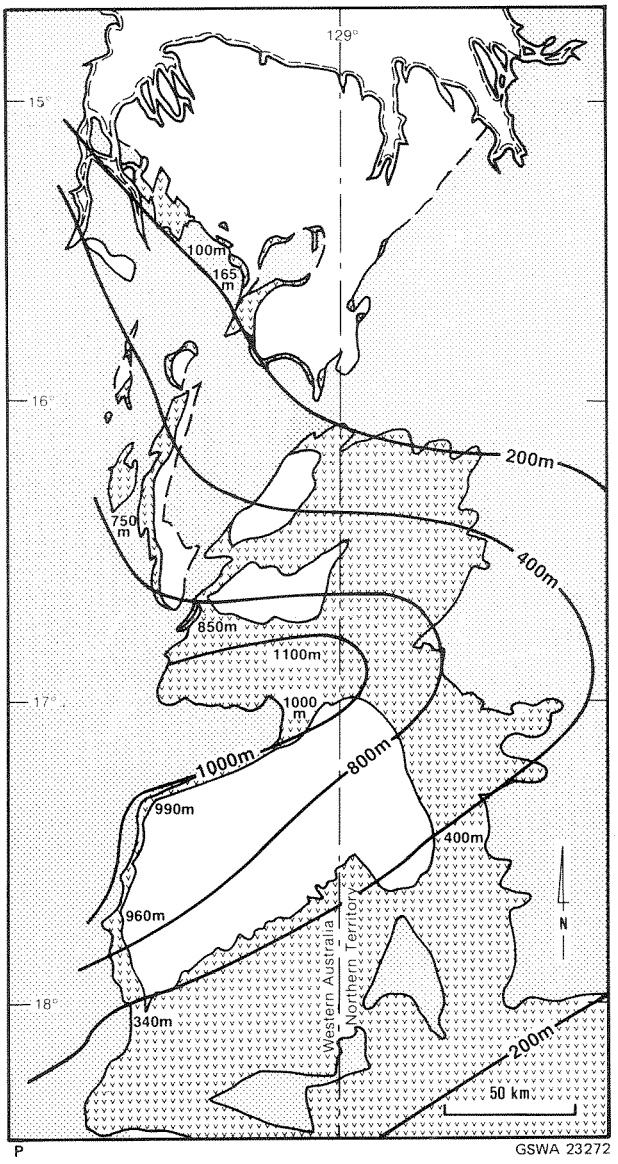


Figure 13. Distribution and thickness of the Antrim Plateau Volcanics (shown by v-pattern) in the Bonaparte and Ord Basins.

the Antrim Plateau Volcanics consist of two flows each approximately 80 m thick (Fig. 29). Medium-grained porphyritic flows are thinner (10–20 m) than other basalt flows, with a high proportion of each flow being vesicular.

In general, flows near the base of the Antrim Plateau Volcanics tend to have a much more restricted distribution than those mapped near the top of the unit. This is probably due to the irregular surface below the volcanics, which may have restricted the area over which individual flows could initially spread.

Fossils and age: The only fossils recovered from the Antrim Plateau Volcanics are the stromatolites *Conophyton basalticum* and *Conophyton* cf. *gaubitza* (Walter, 1972), from the Mount Close Chert Member, which are not diagnostic of a particular age. The age of this unit is determined from its stratigraphic relationship with enclosing units.

The Antrim Plateau Volcanics overlie Proterozoic rocks, locally with an angular unconformity. Thus the isotopic age of 650 Ma from the Albert Edward Group (Bofinger, *in* Dow, 1980) and the Middle Cambrian age of the overlying Goose Hole Group (Öpik, 1967) suggest an Early Cambrian age for the unit.

Depositional environment: Tholeiitic or flood basalts erupted relatively quietly from fissures developed in zones of crustal tension (Macdonald, 1972; Bultitude, 1976). Eruptive centres for the Antrim Plateau Volcanics have not been recognized but the greatest thicknesses of the unit are along the edge of the Halls Creek Mobile Zone, suggesting that the major eruptive centres may have been along this zone. Bultitude (1976) suggests that lack of identifiable eruptive centres "resulted from the burying of any vents by the superposition of thickening lava flows during the later stages of the eruption". The Blackfella Rockhole Member, at the top of the Antrim Plateau Volcanics, has a widespread distribution. This indicates that the flows in this unit were relatively fluid and that the surface over which they flowed had a subdued topographic expression. Flows near the base of the Antrim Plateau Volcanics, by comparison, are not nearly so extensive, due to the presence of palaeovalleys into which the volcanics were initially restricted (Traves, 1955). Eolian sandstone in the Antrim Plateau Volcanics, *e.g.* near Eclipse Yard in the Bonaparte Basin (Fig. 11) and occurrences reported by Sweet and others (1974), indicate that the enclosing basalts were deposited in a continental environment. The conical stromatolites in the Mount Close Chert Member are morphologically similar to those forming today in the hot springs of Yellowstone National Park in the United States. They were possibly also deposited in such an environment rather than under marine conditions (Grey, 1985).

GOOSE HOLE GROUP

The Goose Hole Group (Mory and Beere, 1985) is named after Goose Hole on the Ord River and incorporates all sediments considered to be of Cambrian age within the Ord Basin. It comprises the Negri Subgroup (Negri Group of Traves, 1955) and the overlying Elder Subgroup (previously the ?Devonian Elder Sandstone, in part; Fig. 8)

The Goose Hole Group outcrops in three asymmetric synclines: Hardman, Rosewood, and Argyle (Fig. 6). Exposures of other than the resistant limestone units are rare in the latter two synclines. In the Hardman Syncline the Goose Hole

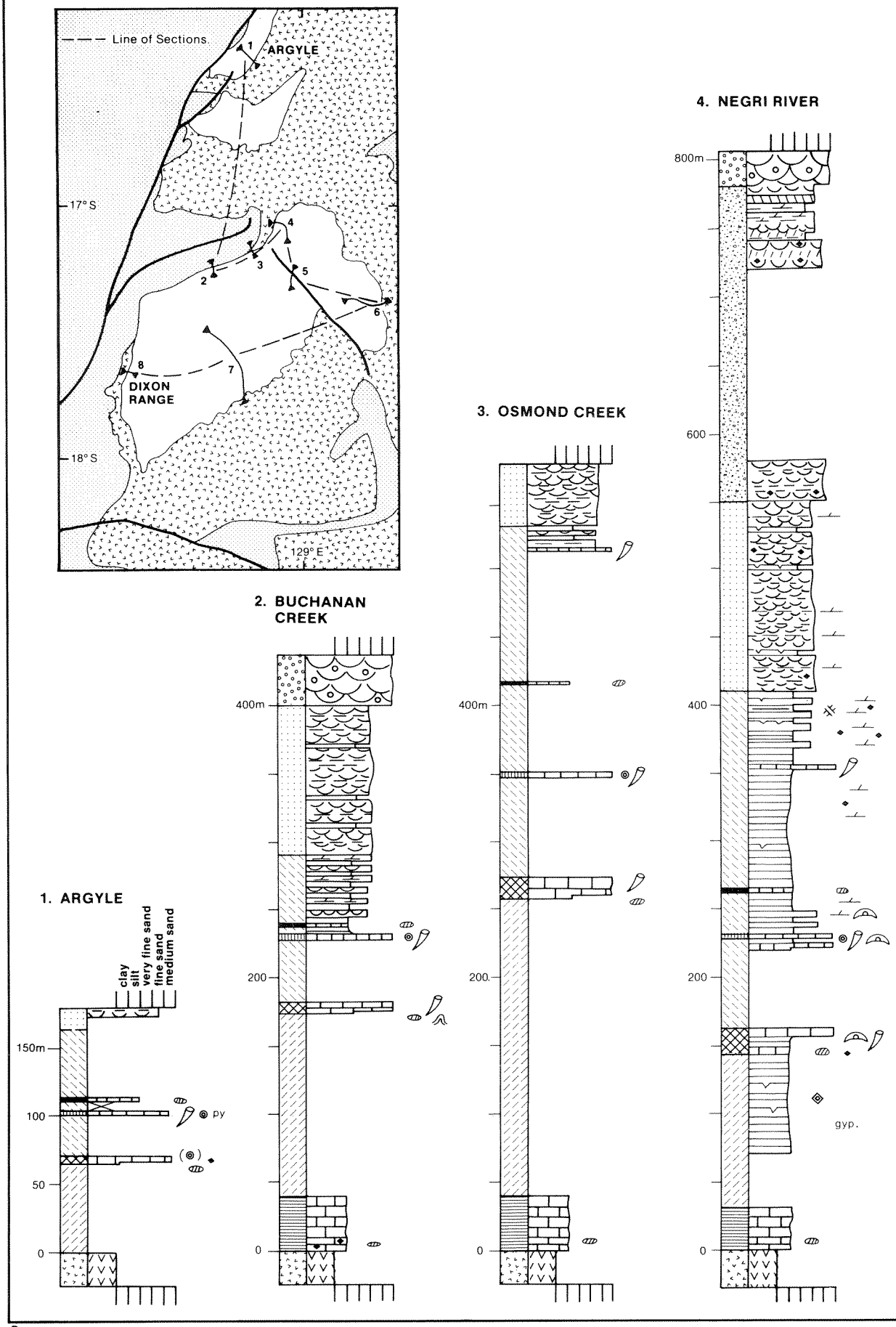
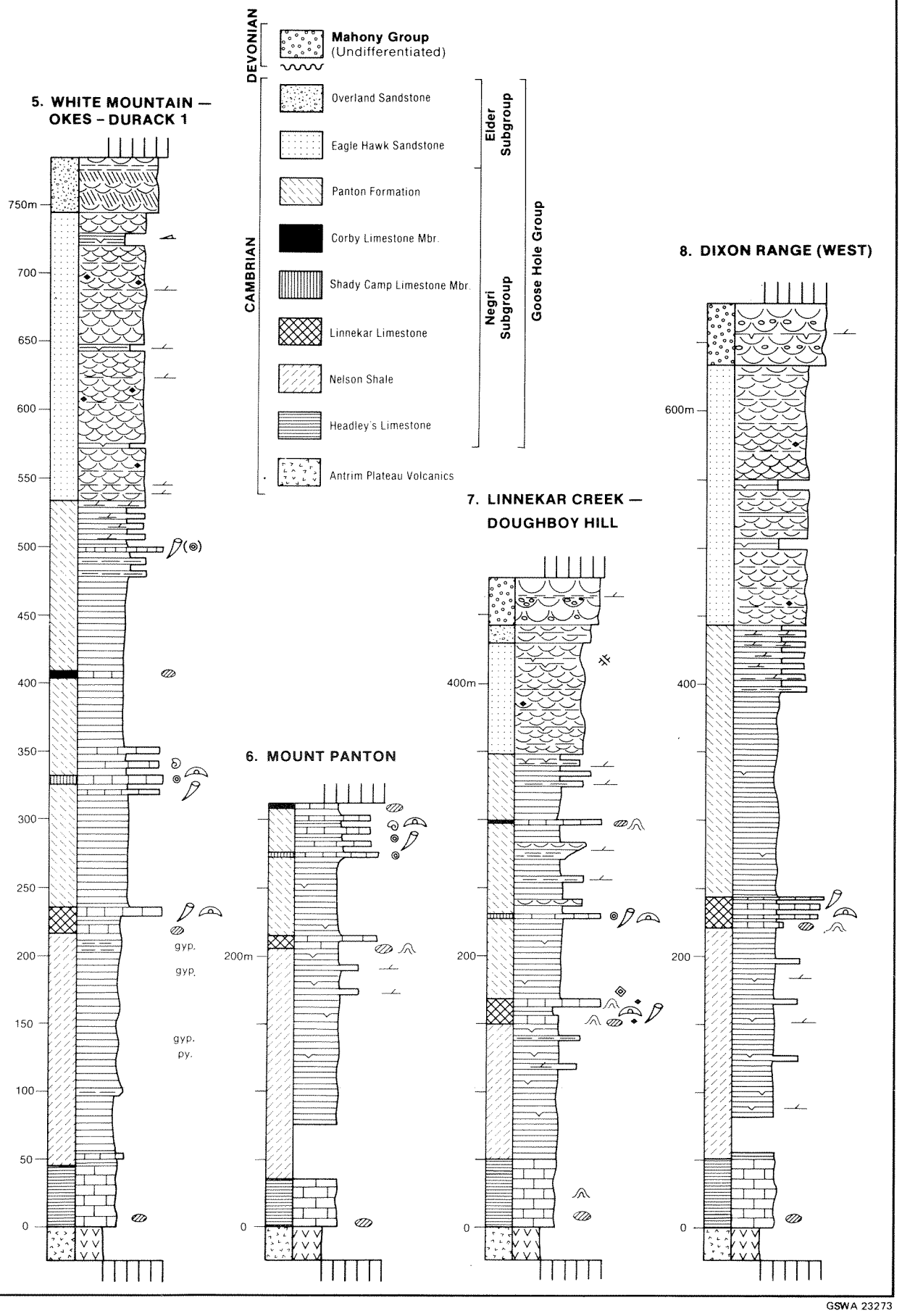


Figure 14. Measured sections of the Goose Hole Group (Cambrian). See Figure 3 for key to symbols.


DEVONIAN
CAMBRIAN
Mahony Group
(Undifferentiated)
Overland Sandstone
Eagle Hawk Sandstone
Panton Formation
Corby Limestone Mbr.
Shady Camp Limestone Mbr.
Linnekar Limestone
Nelson Shale
Headley's Limestone
Antrim Plateau Volcanics
Elder Subgroup
Negri Subgroup
Goose Hole Group
5. WHITE MOUNTAIN — OKES – DURACK 1
750m
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
gyp.
gyp.
gyp.
py.
6. MOUNT PANTON
200m
0
7. LINNEKAR CREEK — DOUGHBOY HILL
400m
200
0
8. DIXON RANGE (WEST)
600m
400
200
0

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Group varies in thickness from 700 m, in the White Mountain–Negri River sections, to 500 m in the Linnekar Creek section. In the Argyle Syncline the group is inferred to be 180 m thick (Fig. 14) but is now largely covered by Lake Argyle. In the Rosewood Syncline the thickness of the Goose Hole Group is similar to that in the Argyle Syncline, although the Elder Subgroup is not present.

NEGRI SUBGROUP

The stratigraphy of the Negri Subgroup was dealt with previously by Mory and Beere (1985) and is discussed only briefly here. Additional sedimentological information follows the stratigraphic description of formations and is presented in terms of facies associations.

The Negri Subgroup was originally called the "Negri series" by Mahony (1922) and refers to the "limestone, mudstone, and shale" which overlie the basalts. It is thus equivalent to the Negri Group of Traves (1955) and Dow and others (1964).

The Negri Subgroup overlies the Antrim Plateau Volcanics with apparent conformity and is, in turn, conformably overlain by the Elder Subgroup. In the Hardman Syncline the Negri Subgroup varies in thickness from 290 m, near Buchanan Creek, to 530 m at Osmond Creek and White Mountain (Fig. 14). In the Argyle Syncline the subgroup is inferred to be 160 m thick from dips of resistant limestone beds; the intervening shale units are very poorly exposed.

The units which make up the Negri Subgroup are (in ascending order) Headleys Limestone, Nelson Shale, Linnekar Limestone, and Panton Formation.

HEADLEYS LIMESTONE

Definition: The Headleys Limestone was named by Traves (1955) after Headleys Knob and consists of grey, laminated or massive micrite with chert nodules (Traves, 1955). The type section is in the vicinity of Headleys Knob from 170°30′25″S, 129°01′25″E (base) to 17°27′25″S, 129°00′25″E (top).

Stratigraphic relationships: The lower contact of the Headleys Limestone, with the Antrim Plateau Volcanics, is sharp but concordant and is considered to be conformable. The contact with the overlying Nelson Shale is also abrupt and presumably conformable.

Distribution and thickness: The Headleys Limestone is present at the base of the Negri Subgroup in the Hardman and Rosewood Synclines; it appears to be absent in the Argyle Syncline. The unit varies in thickness from 35 to 50 m.

Fossils and age: The only fossils recovered from the Headleys Limestone are simple non-branching stromatolites. Traves (1955) suggested a late Early or early Middle Cambrian age, based on the stratigraphic position of the unit.

NELSON SHALE

Definition: The Nelson Shale consists of purple siltstone with minor thin beds of sandstone and micrite. The unit was named by Traves (1955) after Nelson Springs and has its type section nearby, from 17°19′20″S, 129°19′15″E (base) to 17°21′10″S, 129°13′20″E (top).

Stratigraphic relationships: In the Hardman and Rosewood Synclines the Nelson Shale conformably overlies the Headleys Limestone and is, in turn, conformably overlain by the Linnekar Limestone. In the Argyle Syncline the unit directly overlies the Antrim Plateau Volcanics but the only section in which the Nelson Shale was exposed (Behn River) is now covered by Lake Argyle.

Distribution and thickness: The Nelson Shale is present in the Hardman, Rosewood and Argyle Synclines; outcrop of the unit in the latter two synclines is practically non-existent. In the Hardman Syncline the unit varies in thickness from 100 to 183 m (Fig. 14).

Fossils and age: The only fossil recorded from the Nelson Shale is *Girvanella* (Dow, 1980). The Middle Cambrian age suggested by Traves (1955) is based on its stratigraphic position below the fossiliferous Linnekar Limestone.

LINNEKAR LIMESTONE

Definition: The Linnekar Limestone was named after Linnekar Creek by Traves (1955) and consists of fossiliferous limestone and shale. The type section is near the junction of Linnekar and Brook Creeks at 17°32′50″S, 128°42′35″E.

Stratigraphic relationships: The unit lies conformably between the Nelson Shale (below) and the Panton Formation (above).

Distribution and thickness: The Linnekar Limestone is present in all three synclines in the Ord Basin and is between 8 and 24 m thick.

Fossils and age: The presence of *Redlichia forresti* in this unit has been interpreted by Öpik (1967) as indicating an early Middle Cambrian age. In China, however, *Redlichia* is restricted to the Early Cambrian (Zhang and Lin, 1980) suggesting that this formation, and the Negri Subgroup, may be Early Cambrian in age. Other fossils present are *Girvanella, Biconulites hardmani* and unnamed stromatolites.

PANTON FORMATION

Definition: The Panton Formation is a unit of purple siltstone, flaggy sandstone and limestone, which lies conformably between the Linnekar Limestone (below) and the Elder Subgroup (above). The formation includes Traves' (1955) Panton Shale, Shady Camp Limestone, Negri River Shale, Corby Limestone and Hudson Shale, as discussed by Mory and Beere (1985). The type section was designated by Playford and others (1975) at Mount Panton in the Northern Territory (17°16′15″S, 129°12′40″E).

Two members, the Shady Camp Limestone Member and Corby Limestone Member, are recognized. Both of these were given formation status by Traves (1955).

The Shady Camp Limestone Member consists of oncolitic fossiliferous limestone and has its type section at Mount Panton (Mory and Beere, 1985).

The Corby Limestone Member consists of laminated and massive unfossiliferous micrite with chert nodules and lies at a higher stratigraphic level than the Shady Camp Limestone Member. The type section of the Corby Limestone Member is in Hudson Creek at 17°15′35″S, 128°57′20″E (Mory and Beere, 1985).

Distribution and thickness: The Panton Formation is present in all three synclines in the Ord Basin and is best exposed in the Hardman Syncline, where it varies in thickness from 105 to 308 m (Fig. 14). The two limestone members are both less than 4 m thick and, in the Hardman Syncline, lens out to the west and cannot be traced beyond 128°35′E.

Fossils and age: The most fossiliferous part of the Ord Basin sequence is the shale and limestone succession between the Shady Camp and Corby Limestone Members especially in the Mount Panton area. The assemblage of *Redlichia* and *Xystridura* from this part of the Panton Formation is interpreted by Öpik (1967) and Jell (1983) as

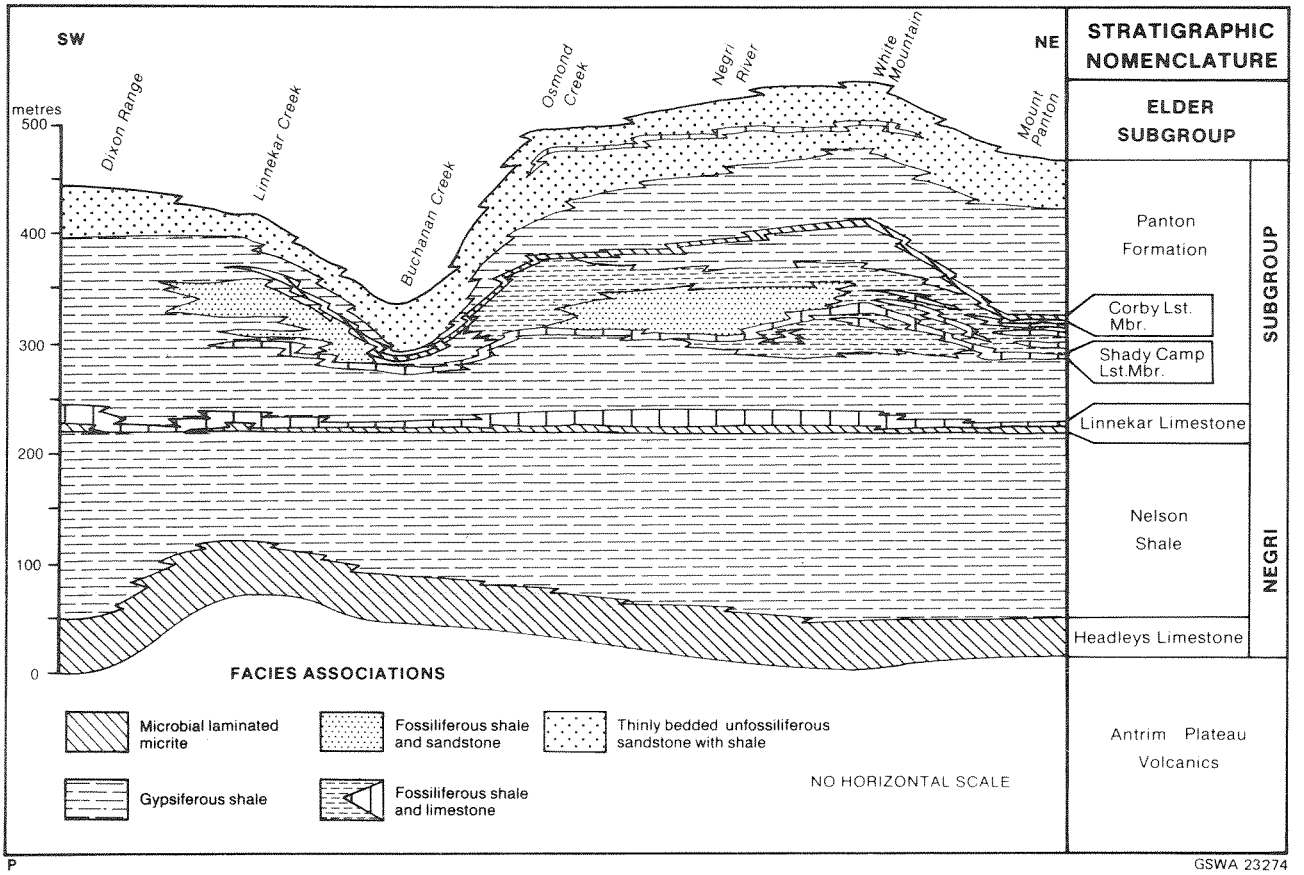

Figure 15. Distribution of facies associations in the Negri Subgroup, across the Hardman Syncline in the Ord Basin. Details of the sections in Figure 14.

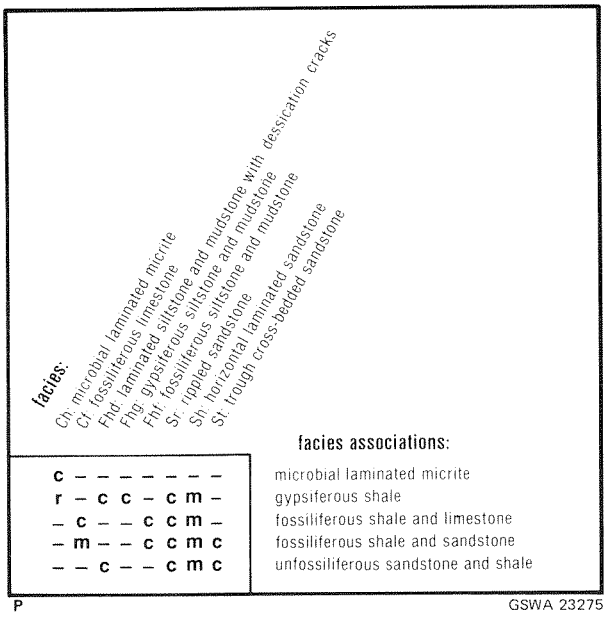

Figure 16. Facies and facies associations in the Negri Subgroup: c-common, m-minor, r-rare.

indicating a Middle Cambrian age. Also reported from this unit are the brachiopods *Billingsella* and *Wimanella*, girvanellids, stromatolites and *Biconulites hardmani* (Traves, 1955).

FACIES ANALYSIS OF THE NEGRI SUBGROUP

The Negri Subgroup comprises five facies associations, three of which are repeated at three different stratigraphic horizons (Fig. 15). These facies associations are: microbial laminated micrite; gypsiferous shale; fossiliferous shale and limestone; thinly bedded fossiliferous shale and sandstone; and thinly bedded unfossiliferous sandstone and shale. Each facies association consists of a number of facies, except for microbial laminated micrite which has only one facies. A total of eight facies are recognized in the Negri Subgroup (Fig. 16).

The microbial laminated micrite facies (*Ch*) consists of laminated and massive grey micrite, with chert nodules common in the more massive sections. As well as the ubiquitous laminated microbial micrites, pustular microbial fabrics and carbonate silt are present. Other distinctive structures in this facies are intraformational breccias and simple stromatolites (Fig. 17). Contacts with enclosing facies are generally abrupt although thin interbeds of laminated siltstone and mudstone, especially at the top of the Headleys Limestone, suggest an interfingering relationship with the gypsiferous shale facies.

The environment of deposition of facies *Ch* was most probably an inter- to supra-tidal flat in which cyanobacteria trapped most of the sediment deposited. Wave and current activity is inferred to be minimal in this facies.

The fossiliferous limestone facies (*Cf*) consists of skeletal mudstone, wackestone and packstone, with *Biconulites hardmani*, oncolites, and trilobites composing the bulk of skeletal fragments. The most common sedimentary structure is crude horizontal bedding; cross-bedding is rare. This facies has gradational contacts with the subfacies *Fhf* (fossiliferous siltstone and mudstone) but has abrupt contacts with the subfacies *Fhd* (laminated siltstone and mudstone with desiccation cracks) and facies *Ch* (microbial laminated micrite) and the sandstone facies *Sr*, *Sh* and *St*.

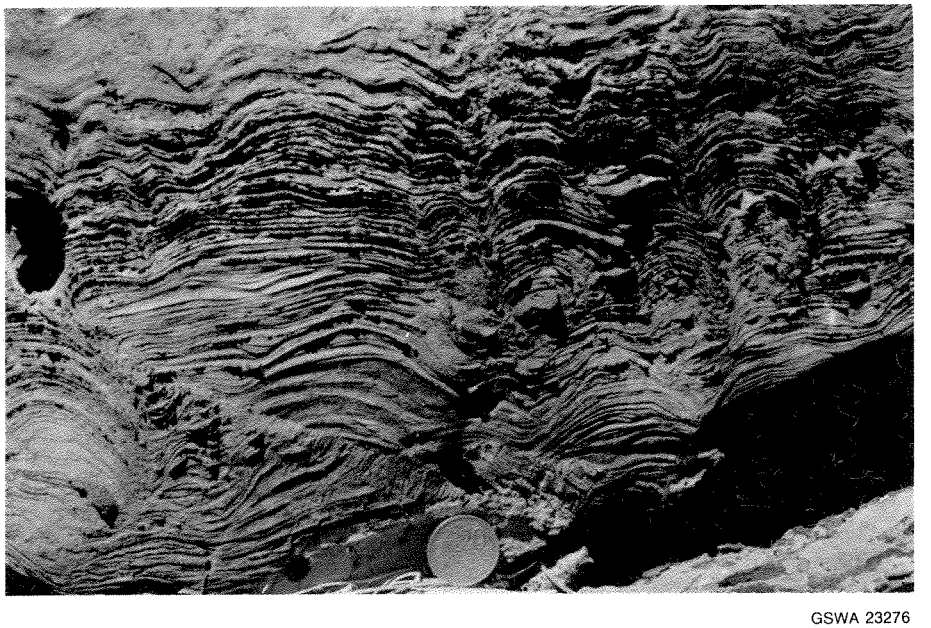

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Figure 17. Pseudocolumnar stromatolites in the basal laminated micrite of the Linnekar Limestone, Dicks Yard, Rosewood Syncline. Coin is 2.8 cm in diameter.

The low diversity of fossils present in this facies suggests a somewhat restricted marine environment. The variation in lithology from skeletal mudstone to packstone and the presence of oncolites suggest intermittent agitation between quiet periods, during which mud-sized carbonate particles accumulated.

The laminated siltstone and mudstone facies (*Fh*) is the most common facies in the Negri Subgroup. The contact between this and other facies is generally abrupt although the presence of interbedded microbial laminated micrite suggests an interfingering relationship between these two facies. Deposition of the laminated siltstone and mudstone facies was from suspension in a quiet environment.

Three subfacies may be recognized in this facies: laminated siltstone and mudstone with desiccation cracks (*Fhd*); gypsiferous siltstone and mudstone (*Fhg*); and fossiliferous siltstone and mudstone (*Fhf*). The first of these subfacies is characterized by numerous desiccation cracks predominantly in mudstone. The gypsiferous siltstone and mudstone subfacies is characterized by thin plates of gypsum, generally oriented parallel to the laminae in the enclosing siltstone and mudstone. In the fossiliferous siltstone and mudstone subfacies, trilobites and *Biconulites hardmani* are common.

The ripple cross-laminated sandstone facies (*Sr*) consists of thin beds of fine- to medium-grained feldspathic sandstone generally with an abrupt but only weakly eroded lower contact. The upper contact of such beds is usually gradational. Horizons of amalgamated ripple cross-laminated sandstone are rare and generally less than 0.5 m thick. Such amalgamated beds are restricted to horizons above the Linnekar Limestone. Ripples in this facies are predominantly wave generated with the remainder being current ripples. Interference ripples are especially common amongst the wave-generated ripples. A shallow, intertidal origin is indicated by associated flat-topped ripples, wrinkle marks and foam impressions, along with desiccation cracks (Figs 18 and 19). For the current ripples, the fine grain size of the sandstone suggests deposition in an upper-flow regime (Harms and others, 1982).

The horizontal-laminated sandstone facies (*Sh*) consists of thin beds of laminated sandstone generally less than 6 cm thick. Sandstone beds belonging to this facies have abrupt lower contacts and gradational to abrupt upper contacts with facies *Fh*. The facies was probably deposited in the plane-bed phase of a high-flow regime (Harms and others, 1982, Figs 2 to 5).

The trough cross-bedded sandstone facies (*St*) consists of horizons of trough cross-bedded sandstone up to 1.5 m thick. Generally the individual cross-beds are less than 10 cm thick and discrete beds of this facies are often enclosed by siltstone and mudstone of facies *Fh* with abrupt upper and lower contacts. Occasionally the upper surface of trough cross-bedded horizons may be modified by facies *Sr* (Fig. 20.) Facies *St* represents migrating sinuous megaripples and, where this facies is restricted to narrow lenticular bodies with strongly eroded lower contacts, such megaripples are presumably infilling small channels.

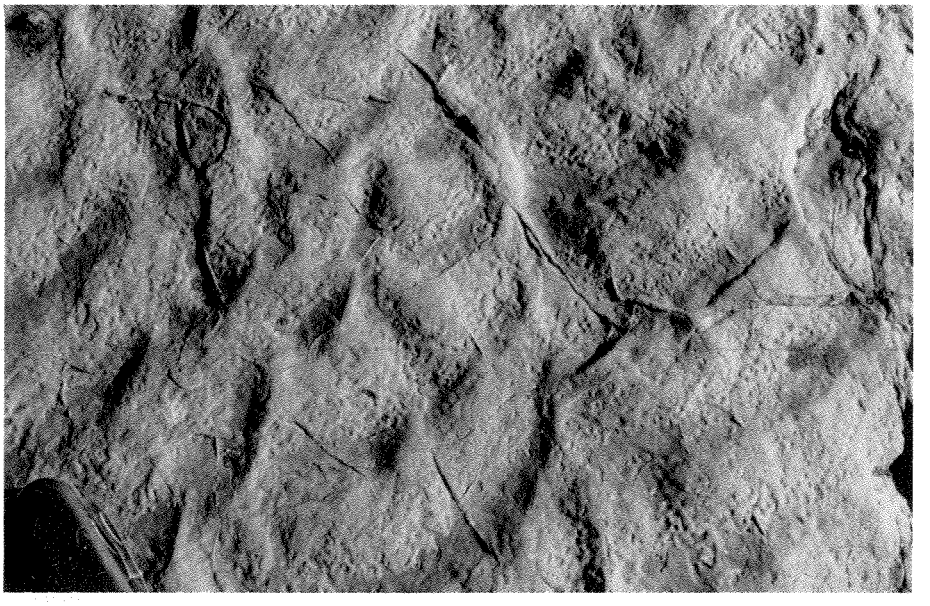

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Figure 18. Foam impressions preserved on the stoss sides of ripples with desiccation cracks. Panton Formation at Negri River crossing, Northern Territory. Knife is 1.5 cm wide.

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Figure 19. **Flat-topped interference ripples in the Panton Formation. Wrinkle marks in the ripple troughs indicate intermittent emergence. Negri River 5 km upstream from its junction with the Ord River. Coin is 2.3 cm in diameter.**

Facies associations

Gypsiferous shale facies association: This association consists predominantly of laminated siltstone and mudstone with gypsum and desiccation cracks (*Fhg* and *Fhd*). Ripple cross-laminated sandstone is also present as well as lesser amounts of horizontal-laminated sandstone and microbial laminated micrite facies. The presence of gypsum and desiccation cracks throughout this facies association indicates tidal-flat sedimentation. Ripple cross-laminated and parallel-laminated sandstone beds represent wave and current-driven influxes of sand, probably deposited during storm activity. Thin beds of microbial laminated micrite accumulated during times of negligible clastic sediment input when cyanobacteria flourished.

Fossiliferous shale and limestone facies association: This contains fossiliferous limestone, laminated siltstone and mudstone (*Cf* and *Fhf*) as well as lesser amounts of ripple cross-laminated and parallel-laminated sandstone. The restricted assemblage of marine fossils present in this association, throughout the Negri Subgroup, suggests deposition in a shallow epicontinental sea.

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Figure 20. **Scour pits on upper surface of festoon cross-bedded sandstone with superimposed interference ripples indicating late-stage emergence runoff. Panton Formation, north bank of the Ord River, 2 km upstream from Parkers Yard.**

Fossiliferous shale and sandstone facies association: The association is similar to the fossiliferous-shale and limestone-facies association, but it contains little limestone and considerably more sandstone including trough cross-bedded sandstone (*St*). Greater substrate mobility is evident from the relative abundance of ripple cross-laminated, parallel-laminated and trough cross-bedded sandstone. A shallow subtidal environment, in which current and wave-driven pulses of sand are not uncommon, is suggested for this facies association.

Unfossiliferous sandstone and shale facies association: This is resticted to the uppermost part of the Negri Subgroup (Fig. 15). It consists of thinly bedded ripple cross-laminated *(Sr)* and trough cross-bedded *(St)* sandstone with lesser horizontal-laminated sandstone *(Sh)* and laminated siltstone and mudstone with desiccation cracks *(Fhd)*. Bioturbation is common, generally consisting of worm burrows and rare trilobite tracks which indicate a marine connection. Sedimentary structures within the ripple cross-laminated sandstone facies clearly indicate late-stage emergence runoff, with sudden changes in flow direction at shallow water depths indicating an intertidal environment of deposition.

DEPOSITIONAL ENVIRONMENT

The Negri Subgroup was deposited in intertidal to shallow subtidal environments. Two distinct marine phases are evident: a basin-wide marine incursion resulting in the deposition of the upper part of the Linnekar Limestone; and a marine incursion from the northwest, in mid-Panton Formation times, which did not reach the southwest end of the basin (Fig. 15). There was little variation in the basin topography during the Middle Cambrian in the Ord Basin. This is suggested by the lateral continuity of limestone units within the Negri Subgroup and the uniform lithology of both limestones and intervening clastic intervals. Such lack of topographic variation is consistent with an intracratonic basin deposited on a stable basement.

ELDER SUBGROUP

Mahony (1922) originally named the "Mount Elder sandstones" after the "red sandstone... which forms a conspicuous chain of hills of which Mount Elder is the most conspicuous point." Subsequent workers have applied the name "Elder" to the entire arenaceous sequence above the Panton Formation. In doing this, they have grouped together sandstones of probable Cambrian age (Elder Subgroup) with sandstones of probable Devonian age (Mahony Group; Mory and Beere, 1985). The Elder Subgroup (Mory and Beere, 1985) consists of a lower, red, micaceous, arkosic sandstone and an overlying white clayey arkose, called the Eagle Hawk and Overland Sandstones, respectively. The Elder Subgroup has a conformable contact with the underlying Panton Formation and is disconformably overlain by the Mahony Group. Although diagnostic fossils have yet to be discovered in the Elder Subgroup, the conformable contact with the underlying Negri Subgroup suggests that the Elder Subgroup is Cambrian in age. In the Hardman Syncline the

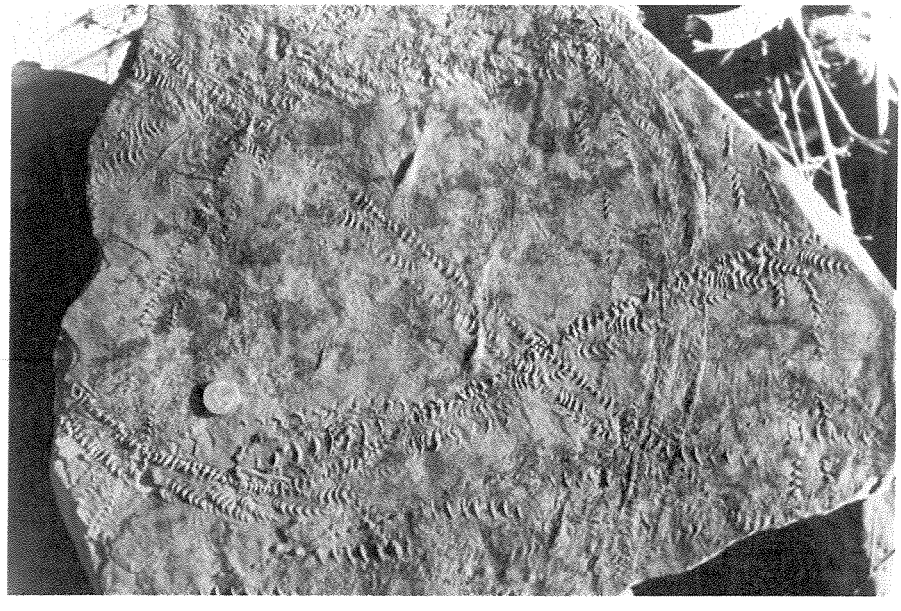

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Figure 21. Cast of trilobite tracks on the lower surface of a bed of *St* facies, from scree of the Eagle Hawk Sandstone. North bank of the Ord River, 1 km upstream from the junction with Osmond Creek. Coin is 2 cm in diameter.

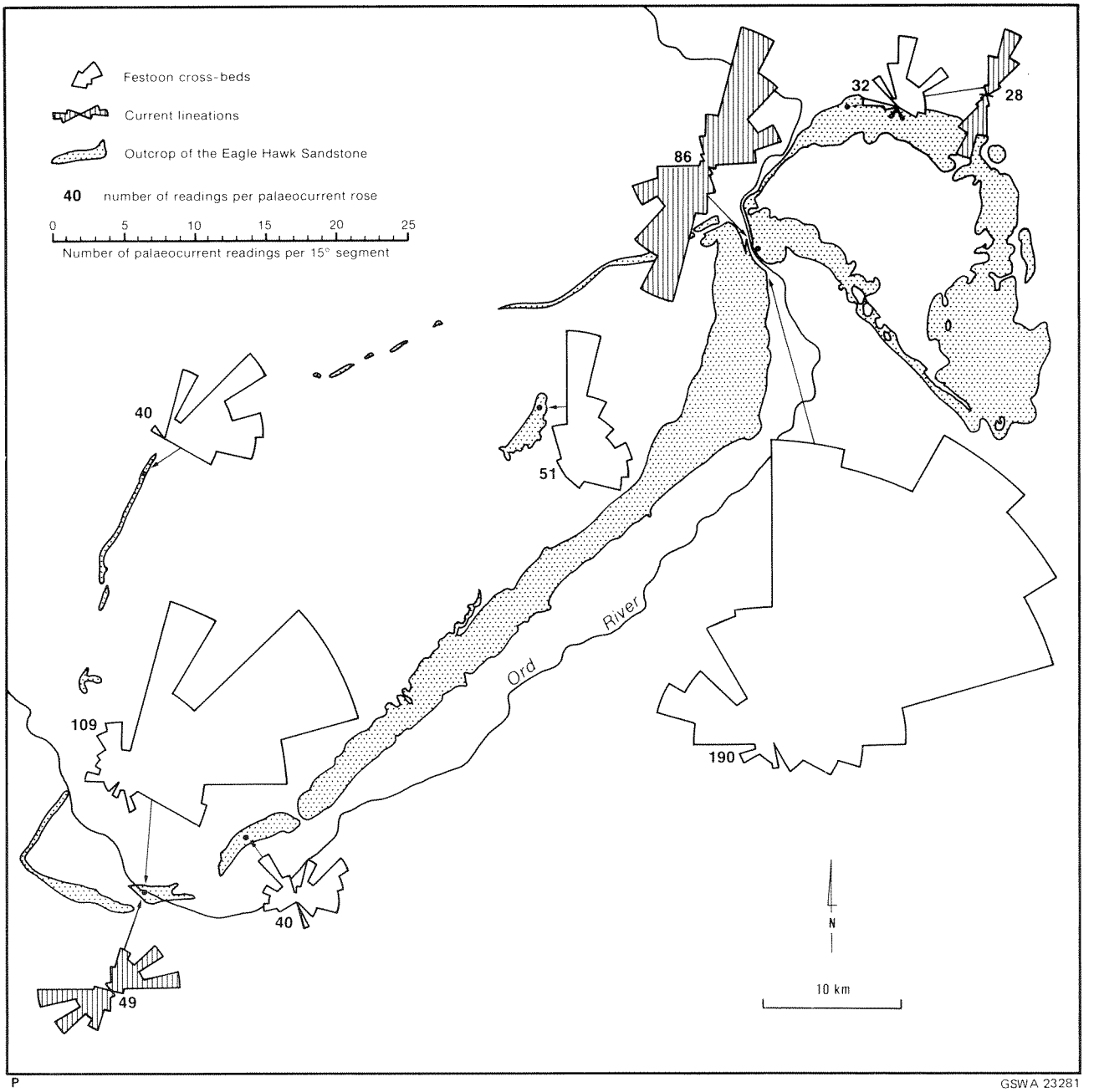

Figure 22. Palaeocurrent directions from facies *St* and current lineations from facies *Sh* in the Eagle Hawk Sandstone, Hardman Syncline.

Elder Subgroup ranges in thickness from 95 m near Doughboy Hill to 370 m just south of the Negri River (Fig. 14).

EAGLE HAWK SANDSTONE

Definition: The Eagle Hawk Sandstone (Mory and Beere, 1985) is a unit of sandstone which conformably overlies the Middle Cambrian Panton Formation. It is conformably overlain by the Overland Sandstone, or, in the absence of the latter unit, is disconformably overlain by the Devonian Mahony Group. The type section is in Hudson Creek from 17°17′45″S, 128°58′45″E (base) to 17°15′30″S, 128°57′30″E (top).

Lithology: The Eagle Hawk Sandstone consists of red, fine-grained, micaceous, arkosic sandstone and minor siltstone and mudstone. In the sandstone many of the feldspar grains are altered but K-feldspar appears to be the dominant variety. Lithic fragments generally constitute less than 3% of the rock and are composed of chert and shale. Accessory detrital minerals include opaques, micas, tourmaline, and zircon. Three facies are recognized: trough cross-bedded sandstone *(St)* parallel-laminated sandstone *(Sh)* and laminated siltstone and mudstone facies *(Fh)*.

The trough cross-bedded sandstone facies *(St)* forms horizons, of medium to thin trough cross-

beds, 0.6 to 15 m thick, with rare angular shale intraclasts. Reactivation surfaces are common. Facies *St* overlies facies *Fh* with an abrupt but rarely eroded contact. Casts of trilobite tracks from the siltstone facies are occasionally preserved on the soles of overlying sandstone beds (Fig. 21). Facies *St* has a gradational upper contact with the *Sh* or *Fh* facies, with interbedding of *St* and *Sh* facies sandstone being common. Trough cross-bedding in facies *St* represents migrating sinuous megaripples or sandwaves in an upper-flow regime. Palaeocurrent directions from this facies (Fig. 22) are predominantly to the northeast, and the southern stations are weakly bimodal with a subsidiary northwesterly direction. This latter direction may represent a transverse set of sinuous dunes, but no morphological distinction from the northeasterly directed set was seen in the field.

The parallel-laminated sandstone facies *(Sh)* consists of beds up to 1 m thick of horizontal-laminated sandstone which may be current lineated. Minor ripple cross-lamination present in this facies may be of either wave or current origin (Fig. 23). Facies *Sh* may be interbedded with facies *St* on a small scale. Where facies *Fh* is present, facies *Sh* generally separates facies *St* below from facies *Fh* above, with gradational contacts. Parting or current lineations are most common in this facies where it is interbedded with facies *St*. These lineations are aligned in a northeast direction (Fig. 22) and probably reflect a similar current direction to the trough cross-bedding in facies *St*. The presence of current lineations in plane bedding in a fine-grained sandstone suggests an upper-flow regime for this facies.

The laminated mudstone and siltstone facies *(Fh)* consist of horizons up to 2.5 m thick of laminated mudstone and laminated siltstone. Commonly within this facies there are sand-filled desiccation cracks up to 8 cm wide with a "keystone" cross-section and a strongly arcuate plan view (Fig. 24). Small sandstone flasers and trilobite tracks are also present in this facies, albeit rarely. Facies *Fh* generally overlies *Sh* or *St* facies sandstone, with gradational contacts, and is abruptly overlain by sandstone of facies *St*. The generally laminated character of this facies suggests slow deposition from suspension. The association of desiccation cracks and trilobite tracks, in laminated fine-grained terrigenous sediment, indicates deposition in an intertidal mud-flat environment. Ripples and sand fillings of desiccation cracks represent localized influxes of small quantities of sand. This probably came from an adjacent sandy environment and was transported by tidal current rather than by storm conditions, since such sands preserve structures present on the surface of the mud flat.

Distribution and thickness: Outcrop of Eagle Hawk Sandstone is chiefly in the Hardman Syncline and in the centre of the Argyle Syncline. In the type section at Hudson Creek the unit reaches a maximum thickness of 210 m. At Doughboy Hill 80 m of Eagle Hawk Sandstone is present and is comparable to the thickness determined by Sweet and others (1974) in the Northern Territory (75 m) for

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Figure 23. Wave-generated ripples on low bar with possible ebb current/interference ripples in foreground. Faint trilobite tracks cover the interference ripples but are not present on the bar. Eagle Hawk Sandstone, north bank of the Ord River, 1 km upstream from the junction with Osmond Creek.

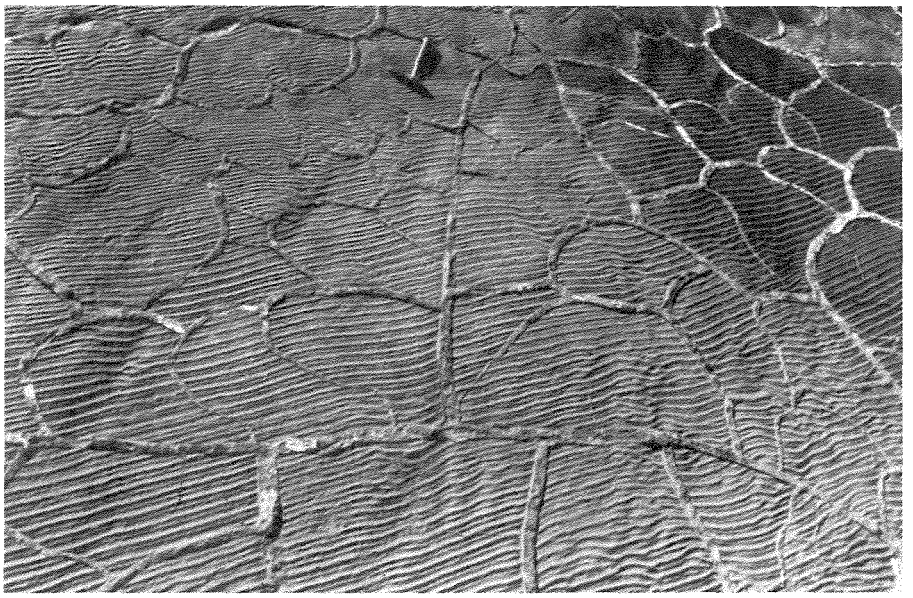

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Figure 24. Wave-generated double-crested ripples intersected by sand-filled desiccation cracks. Numerous trilobite tracks are present on this rippled surface. Eagle Hawk Sandstone, same locality as Figure 23.

their Hudson Formation (equivalent to Eagle Hawk Sandstone in this bulletin); these are the thinnest non-eroded and non-faulted sections in this unit (Fig. 14).

Fossils and age: The only fossils discovered in the Eagle Hawk Sandstone are trilobite tracks, which are not age diagnostic (Fig. 21). The Middle Cambrian age suggested here for this unit is based on its stratigraphic position above the fossiliferous Negri Subgroup. This age is supported by lithological correlation with the Middle Cambrian Hart Spring Sandstone in the Bonaparte Basin, a correlation previously suggested by Traves (1955) for the "Elder Sandstone".

Depositional environment: The close association of trilobite tracks and sand-filled desiccation cracks in the laminated mudstone and siltstone indicates an intertidal mudflat environment for the laminated mudstone and siltstone facies. The presence of wave-generated ripples in the parallel-laminated sandstone and the gradational contact of this facies with facies *Fh* suggests deposition on an intertidal sand flat. Similarly, an intertidal environment of deposition for facies *St* is suggested by the preservation of trilobite tracks on the bases of sandstone horizons in this facies and the generally conformable nature of this contact with facies *Fh*. The absence of obvious cycles within the Eagle Hawk Sandstone further suggests that the three facies are (at least in part) laterally equivalent intertidal environments, with facies *St* representing ebb-dominated migrating sinuous megaripples.

OVERLAND SANDSTONE

Definition: The Overland Sandstone (Mory and Beere, 1985) is a sandstone unit which conformably overlies the Eagle Hawk Sandstone and is disconformably overlain by the Devonian Mahony Group. The name is from Overland Spring, in the Northern Territory, 7 km southeast of the type section which runs from 17°09′15″S, 129°00′15″E (base) to 17°10′55″S, 128°59′50″E (top).

Lithology: The Overland Sandstone consists of unfossiliferous white to fawn, fine- to medium-grained, clayey, lithic arkose and sandstone. Lithic fragments constitute up to 20% of the rock and include quartz-mica schist, fine-grained metasediment, and quartzite. Accessory detrital minerals include well-rounded opaques, muscovite, tourmaline, rutile, and zircon. Three facies are recognized within the Overland Sandstone: trough cross-bedded sandstone (*St*), parallel-laminated sandstone (*Sh*), and planar cross-bedded sandstone (*Sp*).

The trough cross-bedded sandstone facies (*St*) forms persistent tabular horizons, 1 to 15 m thick, which show little lateral variation in internal structures (Figs 25 and 26). The facies consists largely of medium, trough cross-beds with rare sigmoidal foresets and sand-filled channels with sand and shale intraclasts. Where this facies overlies facies *Sh* the contact is abrupt (Figs 26 and 27) with rare load casts forming along the contact. In contrast, vertical contacts with facies *Sp* are generally gradational.

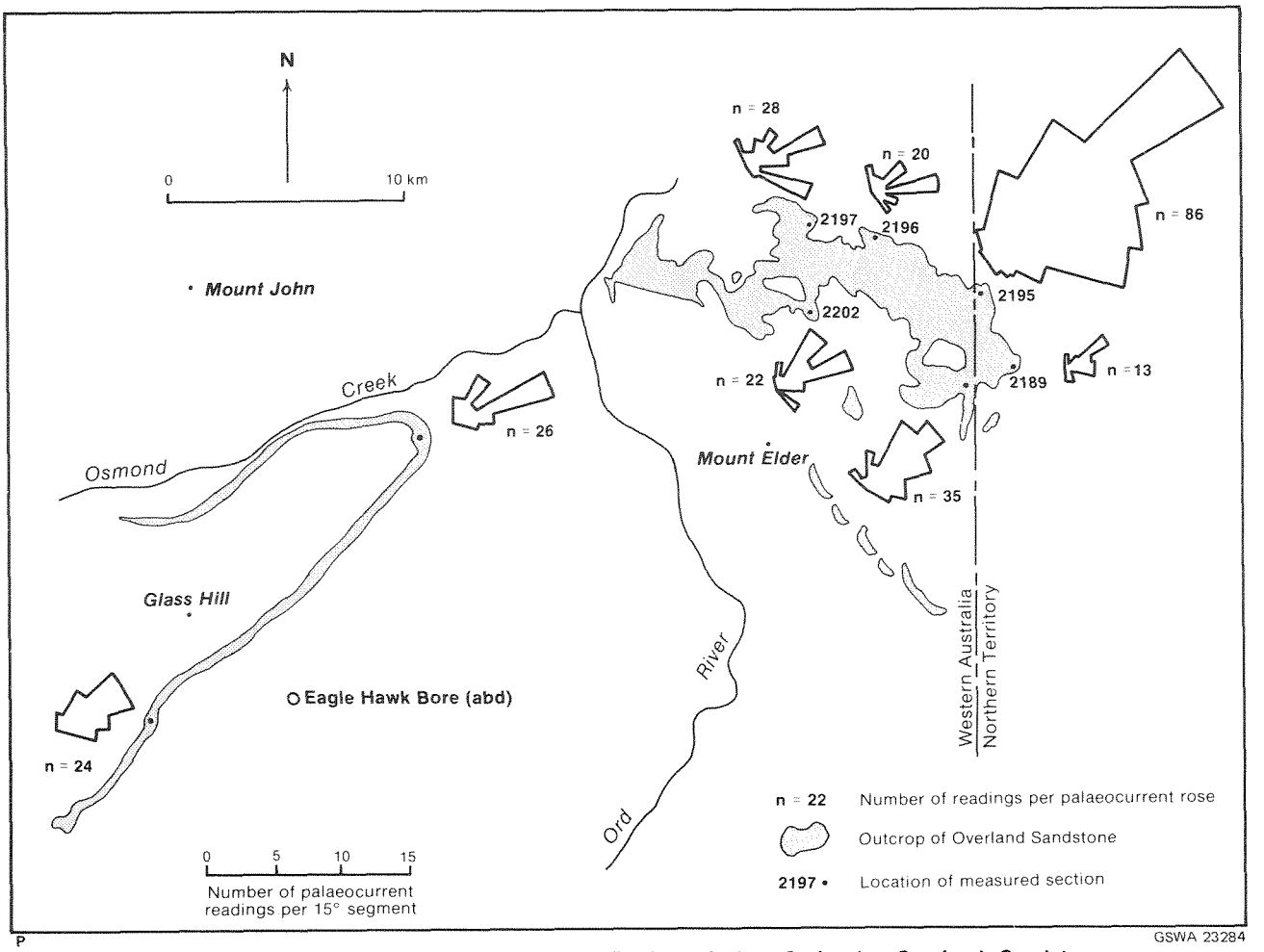

Figure 25. Palaeocurrent directions chiefly from facies *St* in the Overland Sandstone, Hardman Syncline.

The lateral persistence of the trough cross-bedded facies suggests deposition in a laterally uniform environment. Within this environment trough cross-bedding represents migrating sinuous dunes in an upper-flow regime. Load casts at the base of, but rarely within, this facies and the presence of sigmoidal foresets suggest rapid deposition.

The parallel-laminated sandstone facies (*Sh*) forms horizons, 1 to 6 m thick, which pass laterally and vertically into the planar cross-bedded facies. The facies is dominated by parallel-laminated to thin-bedded and low-angle cross-bedded sandstone with common ripple cross-laminations of current origin. Also present are rare trough cross-beds with eroded bases and rippled tops. Thin shale beds occasionally overlie this facies.

The presence of thin interbeds of low- and high-angle cross-beds and ripple cross-lamination indicates that the parallel-laminated facies was deposited by traction currents rather than from suspension (Harms and others, 1982). The generally smaller grain size and dimension of bedforms, compared to facies *St* indicate a lower energy environment due either to waning water velocity or decrease in water depth. Thin shales overlying this facies were deposited during stillstands.

The thick planar cross-bedded sandstone facies (*Sp*) forms beds 3 to 5 m thick in which individual sets are between 1.5 to 5 m high and display asymptotic toesets. Foresets show grainfall lamination and generally have dips of less than 15° (Fig. 28). Palaeocurrent data suggest that the bedforms in this facies are oriented obliquely to the bedforms in facies *St* (Fig. 25). The planar cross-bedded facies appears to pass laterally into facies *Sh* (Fig. 26) and has gradational contacts with both facies *Sh* and *St*.

Facies *Sp* was deposited as large straight-crested dunes or sand waves oriented obliquely to the northeasterly palaeoslope deduced from facies *St*. Grainfall lamination, covering the foresets, is the result of grains settling from suspension on the lee of the bedform. This is due to current separation and suggests high flow velocities.

Distribution and thickness: The chief area of outcrop of the Overland Sandstone is the range of hills north of White Mountain where thicknesses

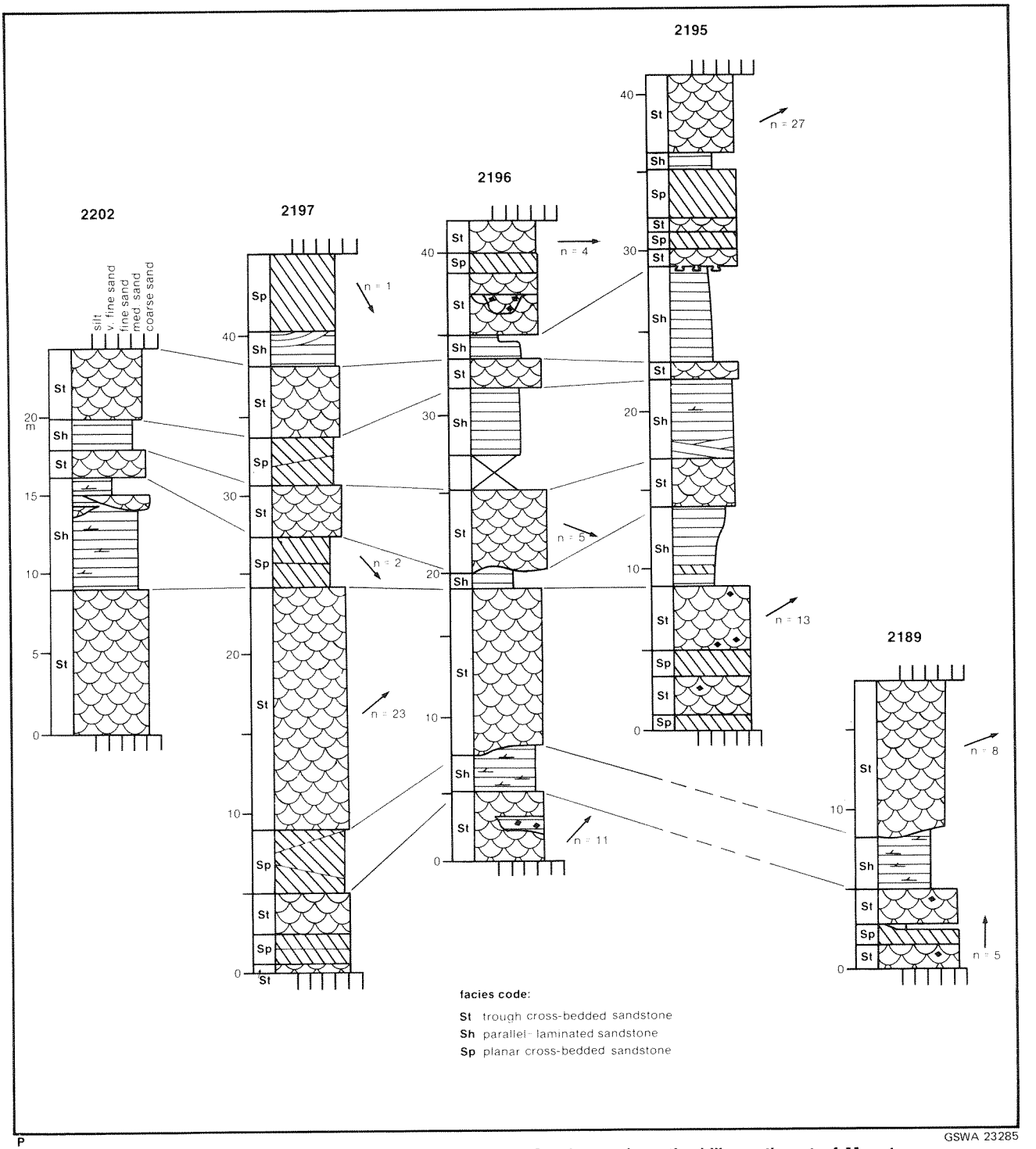

Figure 26. Measured sections in the Overland Sandstone from the hills northeast of Mount Elder. Locations of sections, in Figure 25, key to symbols in Figure 3.

of up to 230 m have been estimated from aerial photographs, although only the uppermost 50 m is well exposed. The unit thins to the southwest, being approximately 10 m thick near Mount Buchanan and Doughboy Hill, and pinches out just north of where the Ord River cuts through Dixon Range. This thinning appears to be the result of erosion prior to the deposition of the Mahony Group. The Overland Sandstone is not known in the Rosewood or Argyle Synclines.

Depositional environment: A fluvial environment is suggested by the sediment immaturity of the Overland Sandstone and the high-energy depositional processes interpreted for each of the three facies recognized in this unit. Laterally extensive sand bodies and the lack of clays deposited from suspension suggest a braided fluvial system. The trough cross-bedded sandstone facies probably formed by the migration of sinuous dunes in channels and as scour fills. Palaeocurrent

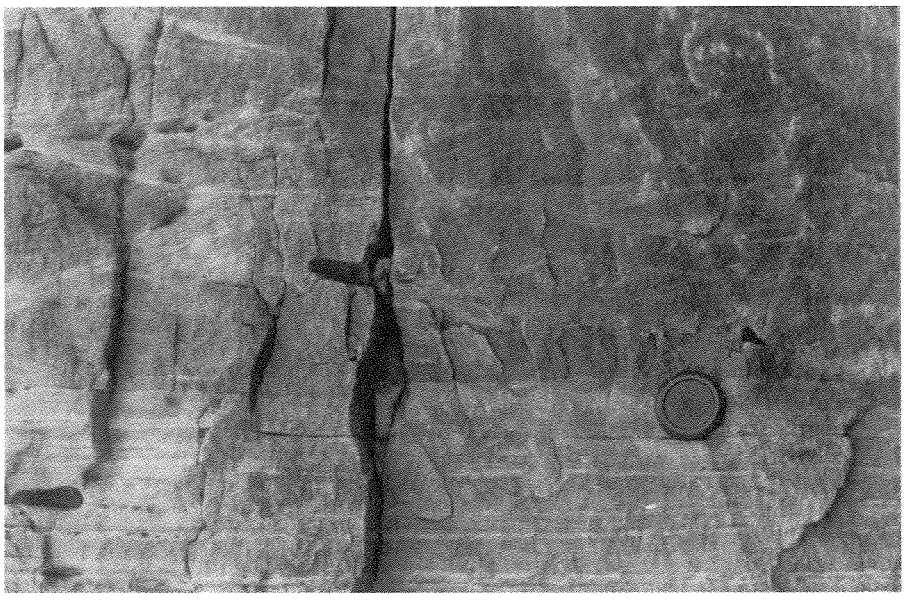

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Figure 27. Abrupt contact between trough cross-bedded (above) and parallel-laminated (below) sandstone facies in the Overland Sandstone, 8 m above the base of section 2189. Location of section in Figure 25.

directions from this facies indicate a palaeoslope to the northeast (Fig. 25). With decreasing energy, either through waning flood conditions or at a different site within the channel system, plane beds were the stable bedform. Large planar cross-beds, with crests oriented obliquely to the main channel sands, represent oblique bars (Harms and others, 1982). Shale horizons formed during stillstands. The lack of pebbles in the high-energy channel sandstones suggests a hinterland of low relief.

CARLTON GROUP

The Carlton Group, previously the "Carlton Series" of Reeves (1949), comprises the Cambrian and Ordovican sequence in the Bonaparte Basin which conformably overlies the Antrim Plateau Volcanics and is disconformably overlain by the Devonian Cockatoo Group. The Carlton Group consists of, in ascending order: the Tarrara Formation; Hart Spring Sandstone; Skewthorpe Formation; Pretlove Sandstone; Clark Sandstone; and

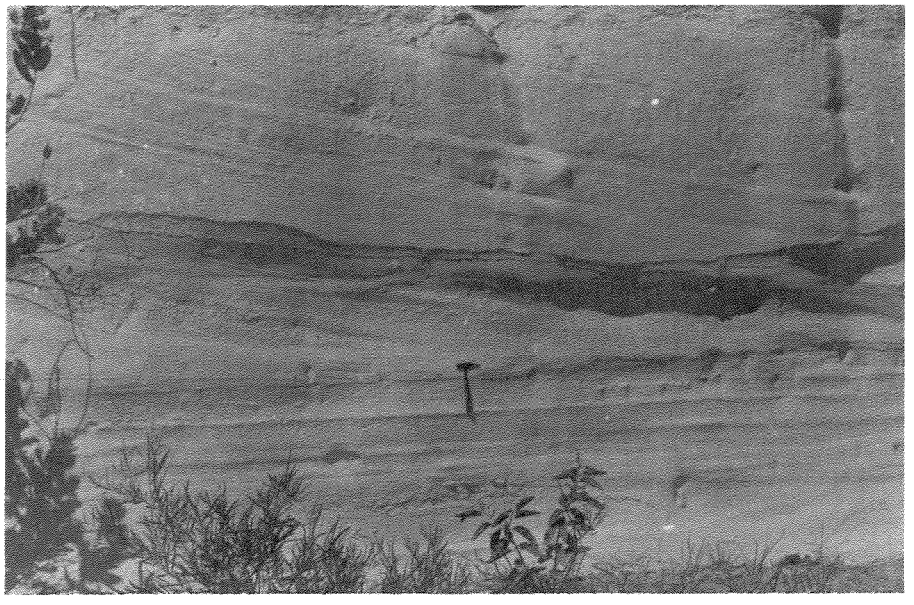

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Figure 28. Contact between planar cross-bedded (above) and trough cross-bedded (below) sandstone facies. Overland Sandstone, eastern side of Dixon Range at 17°39′10″S, 128°25′10″E.

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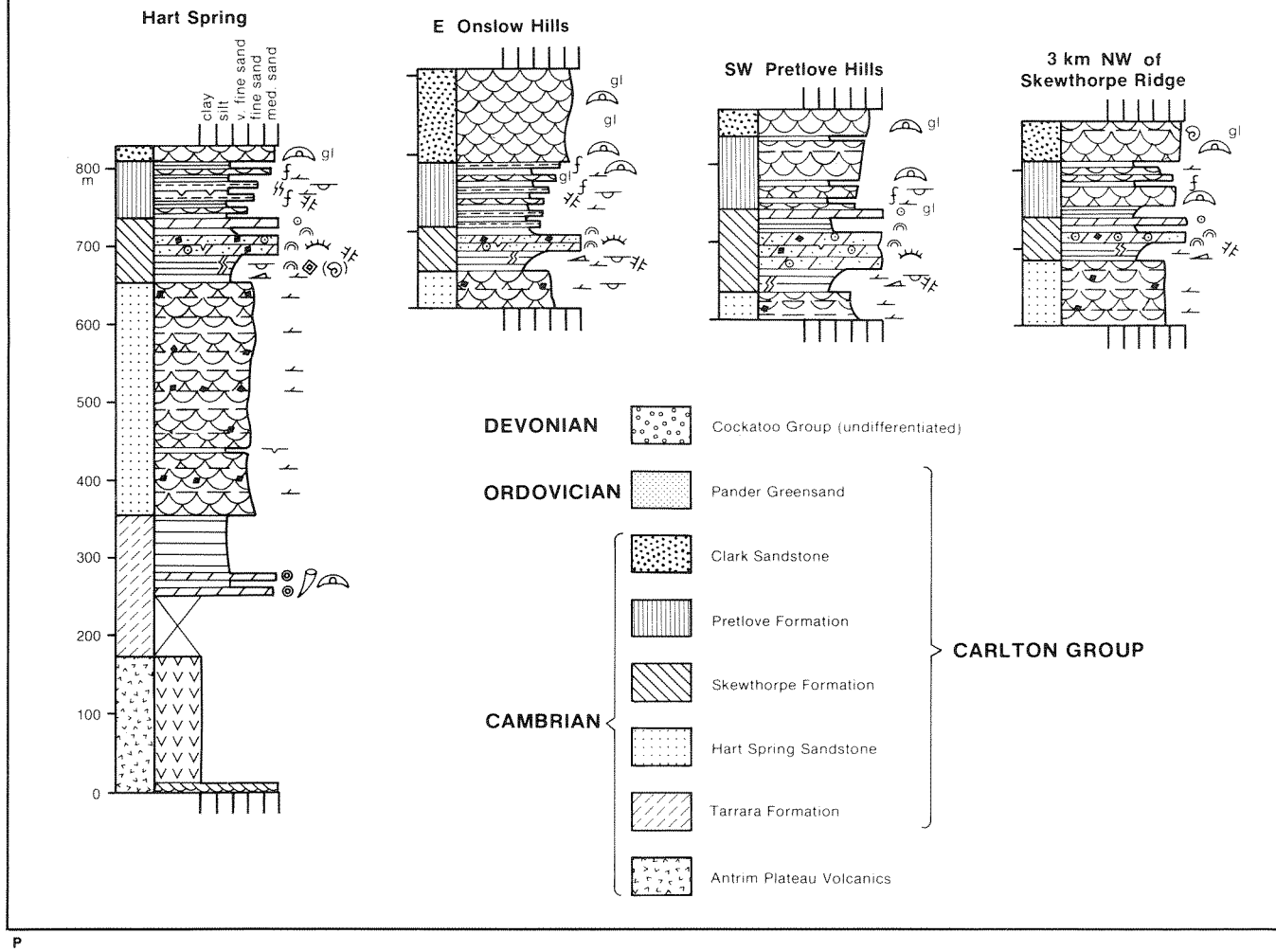

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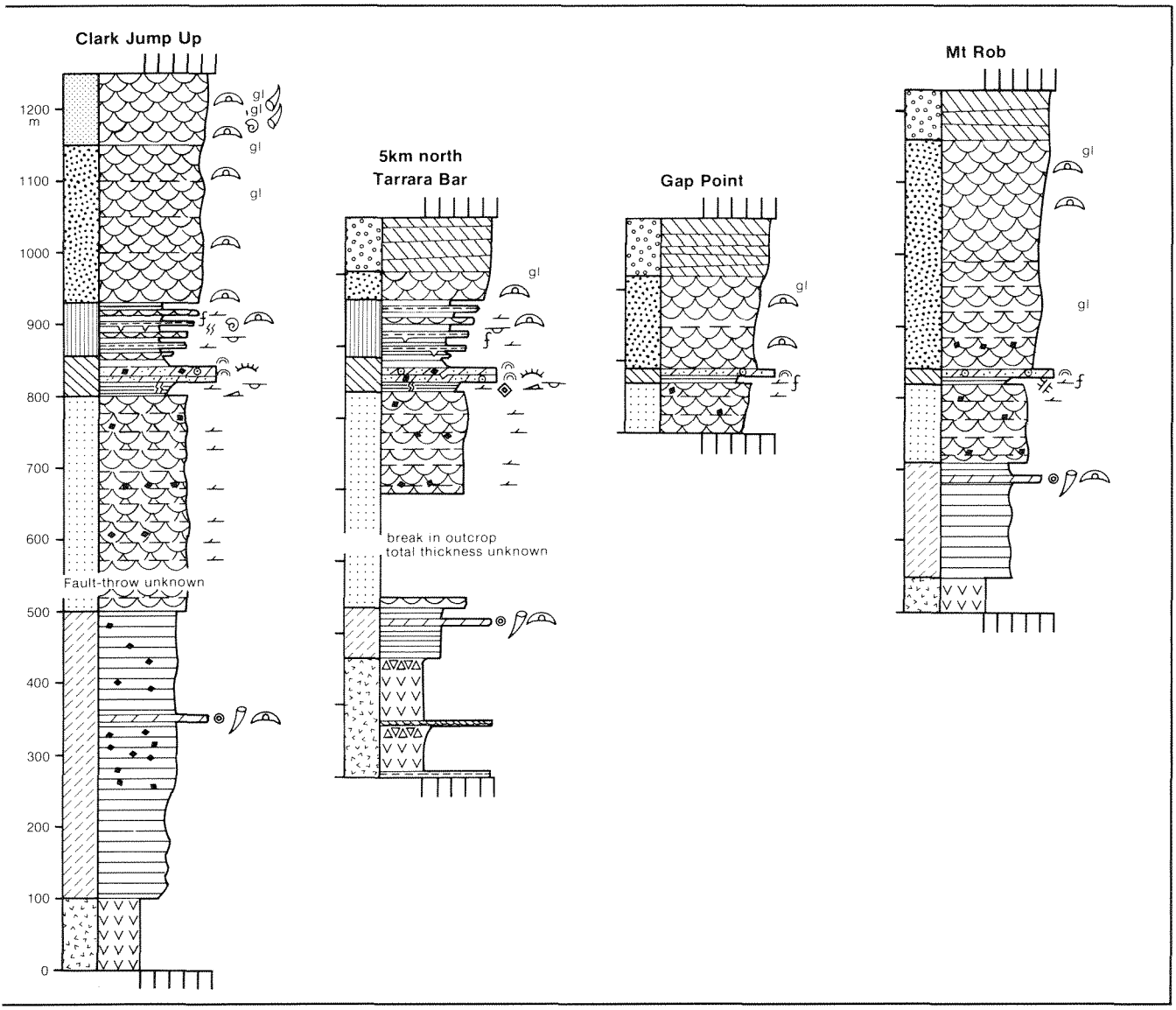
Figure 29. Measured sections of the Carlton Group. Locations of sections in Table 2, key to symbols in Figure 3.

Pander Greensand (Fig. 9). The Carlton Group crops out in a northwest-oriented belt in the Bonaparte Basin (between Mermaid Point and Tarrara Bar) and is also present in the outliers to the south. Within the main outcrop belt, strike faults repeat the sequence up to four times (Fig. 7). In this belt the Carlton Group is approximately 1200 m thick as compared to 600 m at Mount Rob (Fig. 29; Table 2).

TARRARA FORMATION

Definition: Kaulback and Veevers (1969) defined the Tarrara Formation as the "red micaceous silty quartz sandstone, shale and mudstone, and fossiliferous dolomite (which) overlies the Antrim Plateau Volcanics apparently conformably and is conformably overlain by the Hart Spring Sandstone." Kaulback and Veevers (1969, p. 36) located the type section on "the right bank of the Ord River at Tarrara Bar" *i.e.* their section 278 at 15°04′S, 128°41′E. The "Blatchford Formation" (Kaulback and Veevers, 1969) which refers to the Cambrian sequence of the Ragged Range Outlier is here abandoned. Based on lithological similarities with the sequence in the main outcrop belt, the "dolomitic siltstone interbedded with fossiliferous glauconitic dolomite" at the base of the "Blatchford Formation" is here placed in the Tarrara Formation. The remaining "cross-bedded fine-grained brown dolomitic quartz sandstone" is assigned in part to the Hart Spring Sandstone and in part to the Ragged Range Conglomerate.

Lithology: The Tarrara Formation consists of red and grey, laminated, micaceous siltstone and



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mudstone, with silty quartz sandstone and minor grey fossiliferous dolomite. Gypsum crystals have been recorded from this unit in two Western Mining Corporation drill holes, west of Eclipse Yard.

Stratigraphic relationships: The Tarrara Formation overlies the Antrim Plateau Volcanics with an abrupt, but apparently conformable, contact. The upper contact with the Hart Spring Sandstone is conformable and gradational. In the southern part of the Ragged Range Outlier the Tarrara Formation is disconformably overlain by the Devonian Ragged Range Conglomerate.

Distribution and thickness: The Tarrara Formation is very poorly exposed along the southwestern side of the belt of outcrop of the Carlton Group between Mount Connection and Tarrara Bar. The main exposures are west of Buffalo Tank (approximately 160 m in thickness), west of Hart Spring (180 m) south of Clark Jump Up (400 m) and the type section at Tarrara Bar (80 m). The unit is also exposed in the Ragged Range Outlier (60 m), at the base of the Blatchford Escarpment (up to 70 m), and in a creek section in the Mount Rob–Gap Point Outlier (160 m).

Fossils and age: The most fossiliferous horizons in the unit are dolomite beds composed of *Girvanella* and fragments of *Biconulites* cf. *hardmani*. Also present are fragments of the trilobite *Redlichia*, brachiopods, and stromatolites. Öpik (1967) described the metadoxidid trilobite *Onaraspis adjusta* from the base of the Tarrara Formation in the Ragged Range Outlier; this is the only formal published description of a macrofossil from the Carlton Group. Öpik (*in* Kaulback and Veevers, 1969, p.75) assigned an early Middle Cambrian (Ordian) age to this unit.

TABLE 2. LOCATIONS OF MEASURED SECTIONS SHOWN IN FIGURES 29 AND 35

CARLTON GROUP SECTIONS (FIG. 29)

This bulletin		*Latitude (S)* D	M	S	*Longitude (E)* D	M	S	*Kaulback and Veevers (1969) sections*
Hart Spring		15	19	30	128	25	30	209 + 220
	to	15	18	30	128	26	50	(Fig. 3)
East Onslow Hills		15	19	30	128	29	30	236 + 238
	to	15	19	05	128	29	15	(Fig. 3)
Southwest Pretlove Hills		15	25	10	128	33	00	243
	to	15	25	00	128	33	15	
3 km northwest of Skewthorpe Ridge		15	26	20	128	34	40	240
	to	15	26	20	128	35	30	
Clark Jump Up		15	29	35	128	36	55	232 + 245
	to	15	28	15	128	38	00	(Fig. 3)
	and then	15	29	20	128	39	30	
	to	15	29	20	128	40	00	
5 km north of Tarrara Bar		15	31	30	128	40	40	
	to	15	31	00	128	41	00	
Gap Point		16	04	15	128	35	45	275
	to	16	04	05	128	35	35	(Fig. 3)
Mount Rob		15	52	20	128	16	30	274 + 54
		15	52	45	128	15	35	(Fig. 3)

SKEWTHORPE FORMATION SECTIONS (FIG. 35)

This bulletin	*Latitude (S)* D	M	S	*Longitude (E)* D	M	S	*Kaulback and Veevers (1964) sections*	*Traves (1955) localities*
North Onslow Hills	15	16	55	128	27	25	219	
Hart Spring	15	18	40	128	27	00	220	
2 km east of Hart Sp.	15	18	30	128	27	35	221	
East Onslow Hills (S)	15	19	30	128	29	45		
East Onslow Hills (N)	15	19	35	128	29	30	238 (Fig. 21)	
Northeast Onslow Hills	15	18	05	128	29	45	226A (Fig. 3)	
Southwest Pretlove Hills	15	25	05	128	33	05	243	
Northwest of Skewthorpe Ridge	15	26	25	128	34	55	244	
Southeast of Skewthorpe Ridge	15	26	40	128	35	40	240	
Skewthorpe Ridge	15	27	20	128	36	50	201	13
2 km east of Clark Jump Up	15	26	20	128	39	10	235	38
5 km north of Tarrara Bar	15	30	10	128	41	20		
4 km north of Tarrara bar	15	31	15	128	41	00		
Mount Rob	15	54	50	128	15	20	273 (Fig. 3)	

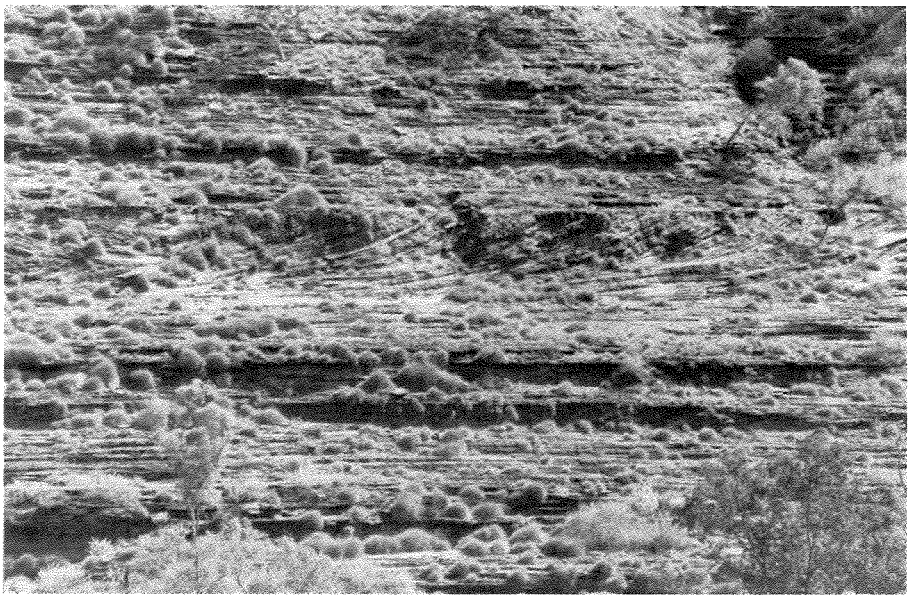

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Figure 30. Large-scale planar cross-bedded sandstone facies (*Sp*), Hart Spring Sandstone at Hart Spring. The upper and lower contacts are concordant with the enclosing *St* and *Sh* facies. The cross-beds (facies *Sp*) are approximately 5 m thick.

Depositional environment: The fossiliferous dolomite in the Tarrara Formation indicates a shallow-marine environment, whereas the presence of gypsum in the enclosing fine-grained clastics suggests an intertidal environment or a shallow epicontinental sea, *i.e.* a depositional environment similar to that of the coeval Negri Subgroup in the Ord Basin.

HART SPRING SANDSTONE

Definition: Traves (1955) defined the Hart Spring Sandstone as "the sandstone with some impure limestone and shale, which crops out in the vicinity of Hart Spring...". Kaulback and Veevers (1969) placed the "impure limestone and shale" in the Tarrara Formation and redefined the Hart Spring Sandstone as "the fine to medium-grained red micaceous quartz sandstone that conformably overlies the Tarrara Formation and is conformably overlain by the Skewthorpe Formation". Neither Traves nor Kaulback and Veevers selected a type section, possibly since they could not find a complete unfaulted section. The type section is here defined as the section adjacent to

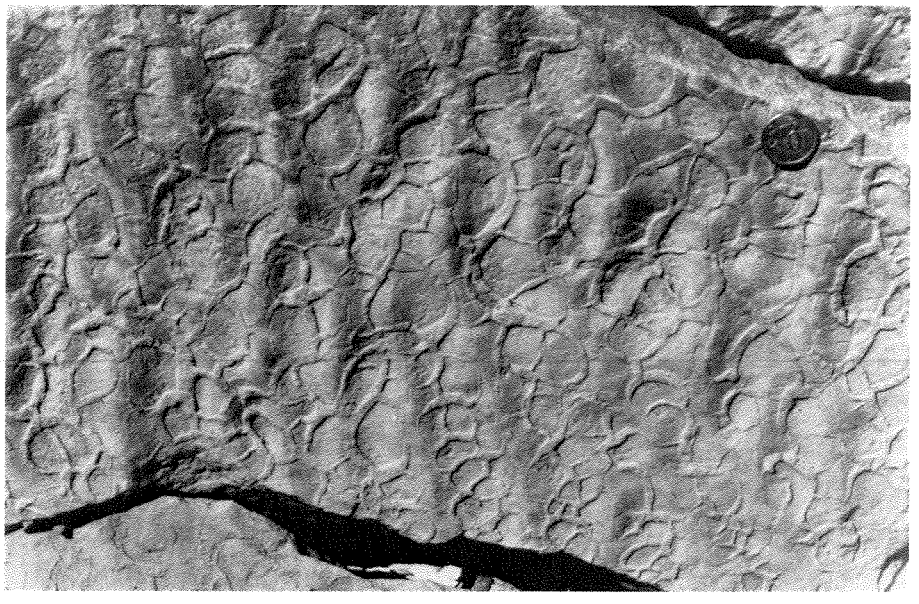

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Figure 31. Bedding-surface view of syneresis cracks concentrated in ripple troughs, Hart Spring Sandstone, eastern Onslow Hills. Coin is 2.3 cm in diameter.

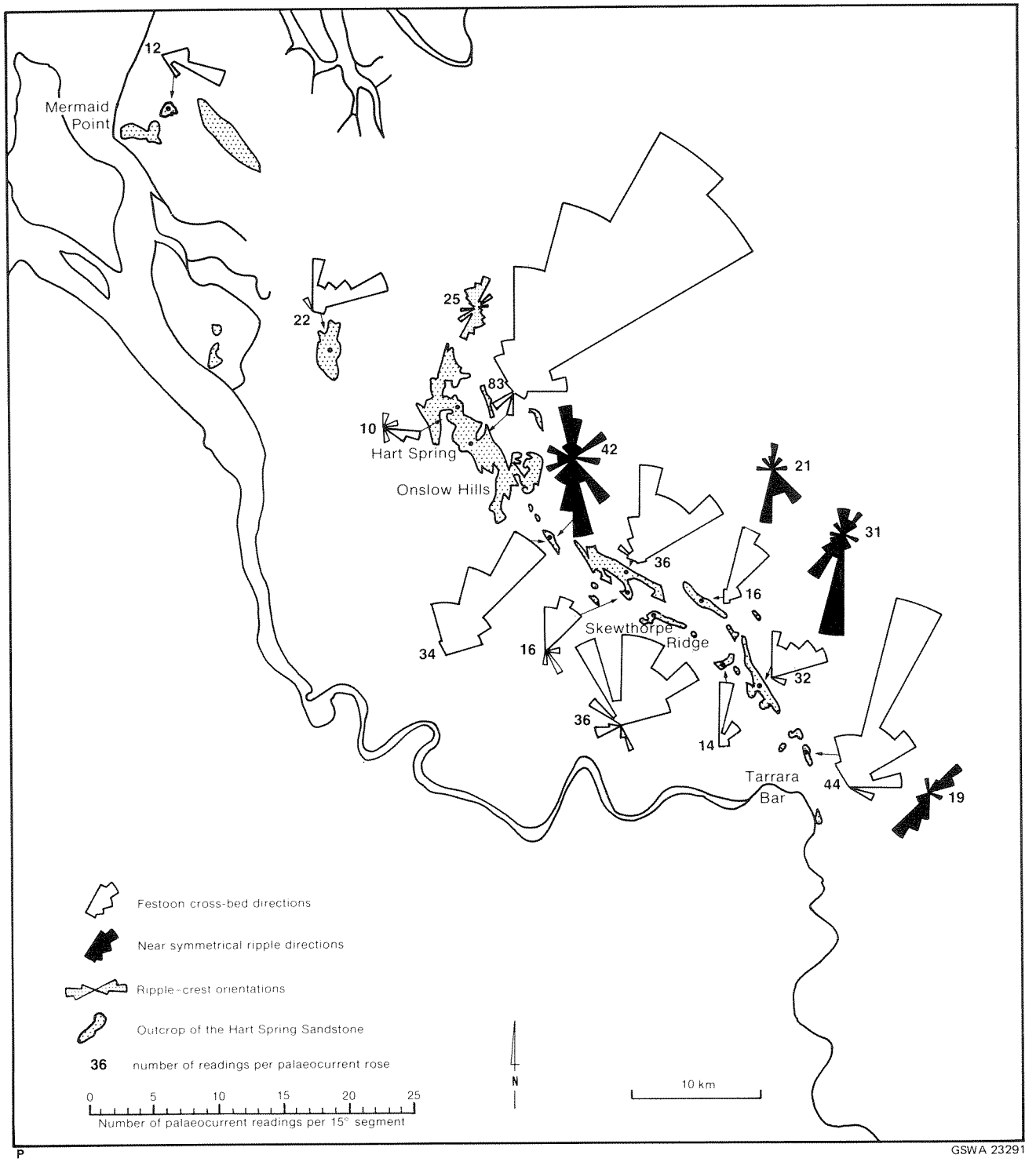


Figure 32. Palaeocurrent directions from facies *St* and *Sh*, in the Hart Spring Sandstone.

Hart Spring from 15°19′10″S, 128°26′10″E (base) to 15°18′50″S, 128°26′45″E (top) being the thickest section with both lower and upper contacts exposed in the nominal area (Fig. 29, Hart Spring section).

Lithology: The Hart Spring Sandstone consists of a uniform sequence of texturally mature, fine-grained, micaceous, quartz sandstone occasionally with a calcareous cement. Siltstone interbeds with sand-filled desiccation cracks are extremely rare. In the sandstone, quartz grains predominate, with lesser quartzite and chert grains. The siliceous grains are often coated with a secondary overgrowth of silica. The grains are mostly well rounded and are coated by a film of iron oxide giving the sandstone a red colour. Accessory detrital minerals include micas, tourmaline, glauconite, and rare opaques. In the sandstone three facies are recognized: thin to medium trough

cross-bedded facies (*St*); thick planar cross-bedded facies (*Sp*); and parallel-laminated facies (*Sh*).

The thin to medium trough cross-bedded facies (*St*) consists of trough cross-beds and structureless sandstone beds 4 to 25 cm thick. Beds of amalgamated trough cross-beds rarely reach a thickness greater than 1 m. Facies *St* interfingers with facies *Sh* with individual cross-beds often enclosed by parallel-laminated sandstone. Near the base of cross-beds, small shale intraclasts are common. Structureless beds included in this facies may have originated from rapid deposition, or they may be festoon cross-beds which have been disrupted by dewatering.

The thick planar cross-bedded facies (*Sp*) consists of discrete very thick beds of planar cross-bedded sandstone with foresets up to 5 m high. In spite of the large size of the foresets this facies is concordant with the enclosing *St* and *Sh* facies (Fig. 30). The large foresets are oriented predominantly to the east-southeast, almost at right angles to the palaeocurrent direction in facies *St*.

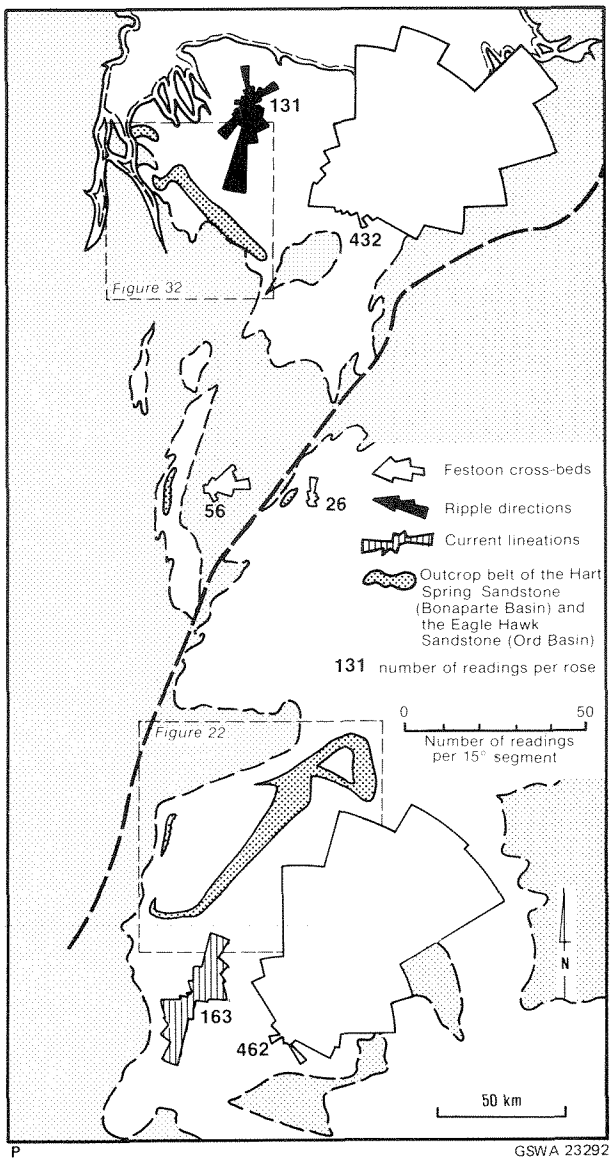


Figure 33. Summary and comparison of palaeocurrent data from the Hart Spring Sandstone (Bonaparte Basin) and the coeval Eagle Hawk Sandstone (Ord Basin).

The parallel-laminated facies (*Sh*) consists primarily of horizontal-laminated sandstone beds, 3 to 40 cm thick, with subordinate ripple cross-laminations and syneresis cracks (Fig. 31). Current lineations are notably absent. Facies *Sh* interfingers with facies *St*, often separating single trough cross-beds giving the Hart Spring Sandstone its even, parallel-bedded character (Fig. 30). Ripples in facies *Sh* are slightly asymmetrical and are mostly (95%) wave generated. Ripple crests are oriented approximately east-west along most of the outcrop belt. Those ripples, for which directions of movement can be determined unambiguously, show a bimodal distribution with approximately 60% of readings to the south and 40% to the north (Figs 32 and 33). From Tanner's (1971) empirical method for calculating ancient wave parameters a water depth of less than 0.5 m is estimated.

Stratigraphic relationships: The Hart Spring Sandstone conformably overlies the Tarrara Formation with a gradational contact. The upper contact with the Skewthorpe Formation, although abrupt, is concordant and is probably conformable.

Distribution and thickness: The Hart Spring Sandstone has a patchy distribution along a northwest-oriented belt in the Bonaparte Basin from Mermaid Point to Tarrara Bar (Fig. 32), also in the Mount Rob–Gap Point, Dillon Spring and Ragged Range Outliers. The unit is approximately 300 m thick in the main belt of outcrop, but thins to 120 m in the Mount Rob–Gap Point Outlier to the south (Fig. 29).

Fossils and age: Since the Hart Spring Sandstone is unfossiliferous, the Middle Cambrian (Templetonian to Boomerangian) age of this unit has been deduced from its stratigraphic position between the Tarrara and Skewthorpe Formations. Fossils reported from the unit (Traves, 1955; Kaulback and Veevers, 1969) are here thought to come from float from the overlying Skewthorpe Formation.

Depositional environment: Opposing palaeocurrent directions in the *St* and *Sh* facies (Fig. 32) suggest a tidal environment. The rarity of fine-grained clastics with desiccation cracks indicates shallow subtidal conditions, in which facies *St* represents ebb-oriented sinuous megaripples or sand waves deposited in an upper-flow regime. While facies *Sh* was probably generated by shoaling waves

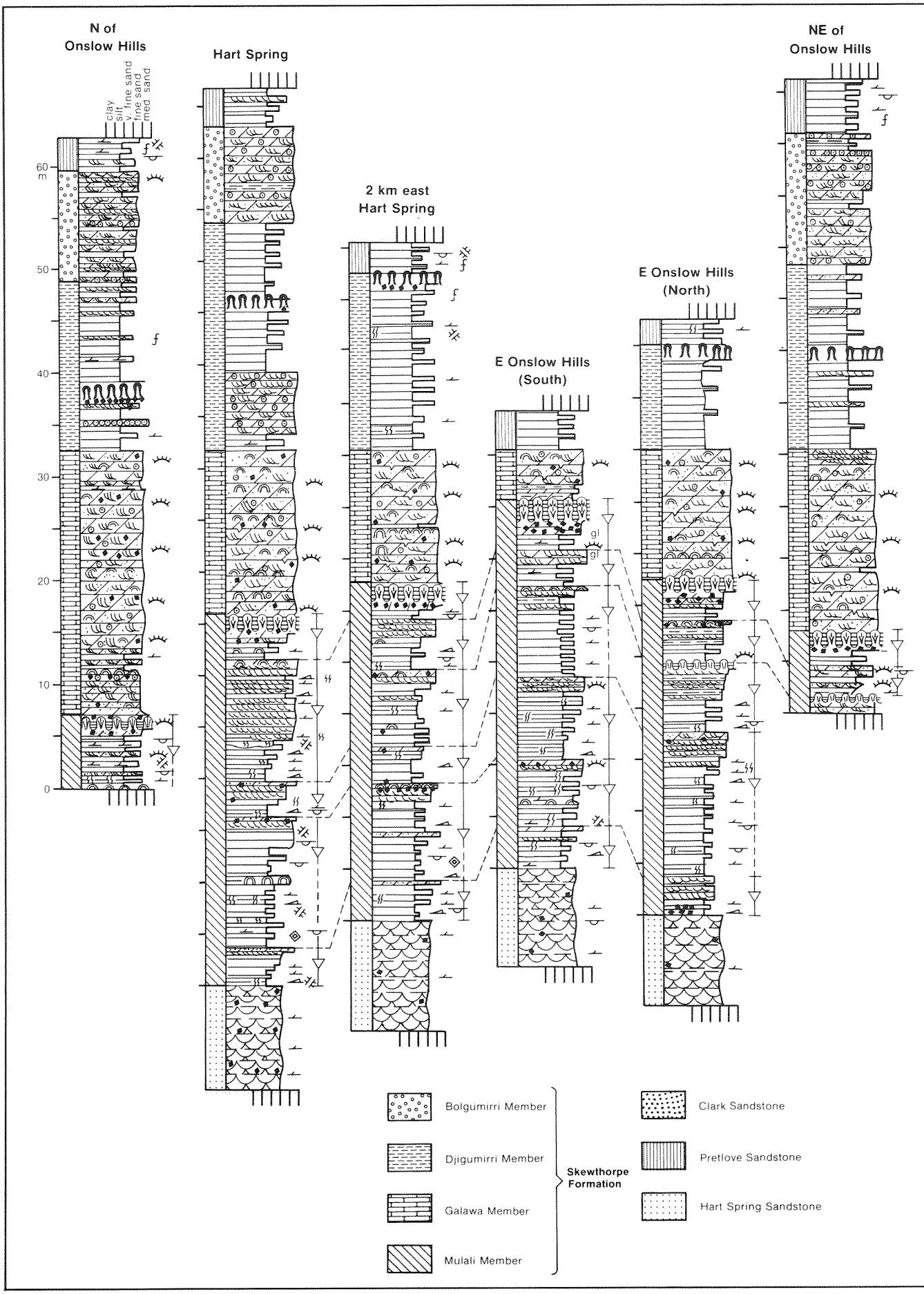
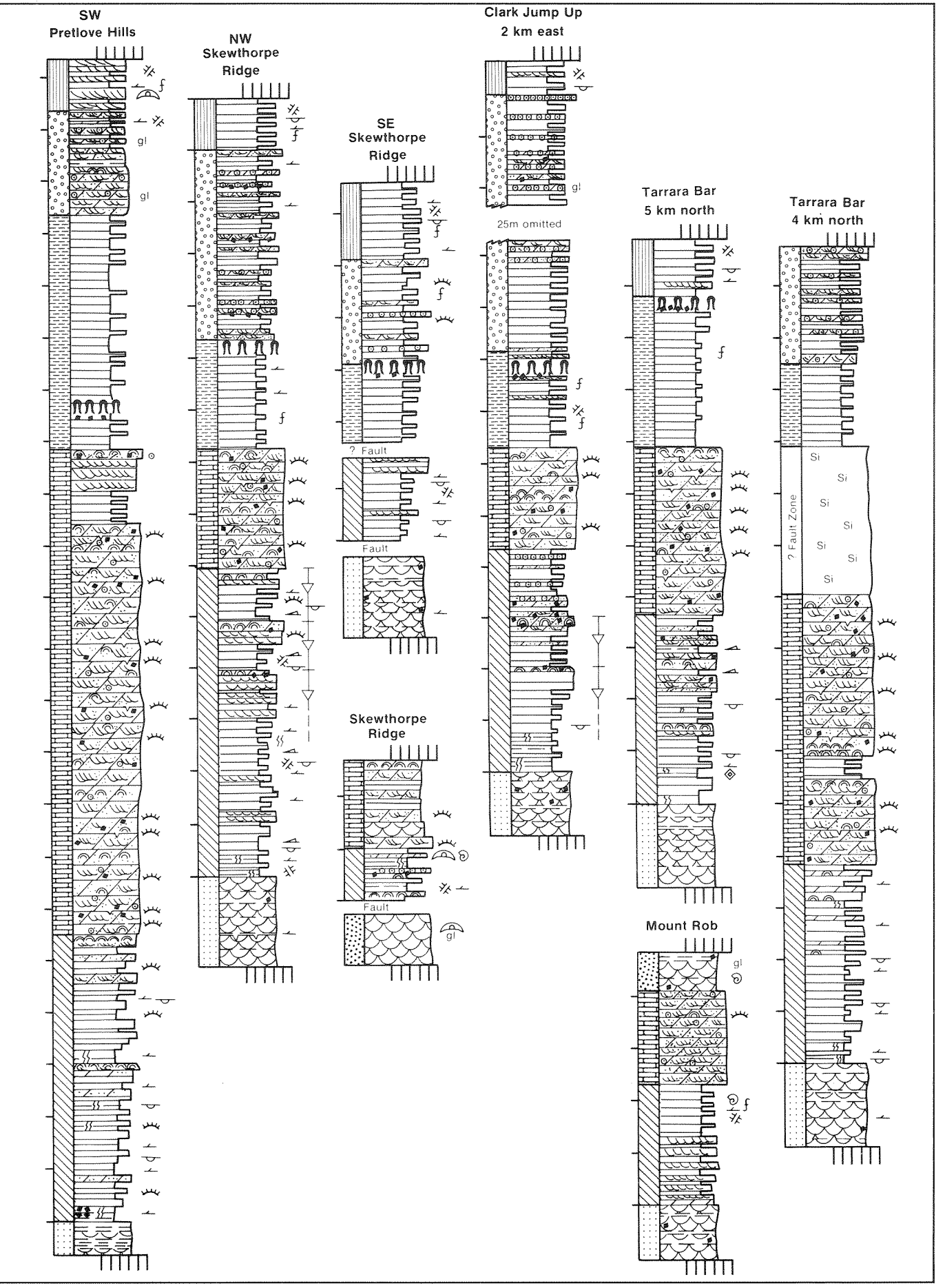


Figure 34. Measured sections of the Skewthorpe Formation. Location of sections in Figure 35, key to symbols in Figure 3.


SW
Pretlove Hills
NW
Skewthorpe
Ridge
SE
Skewthorpe
Ridge
Clark Jump Up
2 km east
25m omitted
Tarrara Bar
5 km north
Tarrara Bar
4 km north
? Fault
Fault
Skewthorpe
Ridge
Fault
Mount Rob
? Fault Zone
Si
gl
f

P

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reworking the tops of megaripples and creating suspension clouds (Reineck and Singh, 1975, p. 106). The near-symmetrical ripples in facies *Sh* probably represent a further modification of the megaripples, produced by small waves that were generated by onshore to offshore reversals in wind direction. Facies *Sp* probably represents large, discrete, tidal, sand waves which moved obliquely across the shelf. Concordant upper and lower contacts of these large sand waves with the enclosing *St* and *Sh* facies suggest that tidal scour was slight.

SKEWTHORPE FORMATION

Definition: Traves (1955, p. 50) gave the name Skewthorpe Formation to "the sediments which crop out at Skewthorpe Ridge . . . characterized by fossiliferous oolitic limestone." The unit is divided into four members, the Mulali, Galawa, Djigumirri and Bolgumirri Members, in ascending order (Beere and Mory, 1986). In their review of the Bonaparte Basin, Playford and others (1975) stated that the type section was at Skewthorpe Ridge although neither Traves (1955) nor Kaulback and Veevers (1969) designated a type section. Skewthorpe Ridge is unsuitable as a type section because small strike faults have removed parts of the unit and have also emplaced a section of Clark Sandstone into the centre of the ridge (Fig. 34, Traves' location 13). The type section is defined as the cliff exposures at Hart Spring from 15°18′45″S, 128°26′50″E (base) to 15°18′35″S, 128°26′50″E (top) being the best exposed section with all four members present.

The Skewthorpe Formation is completly divided into four members (Beere and Mory, 1986).

The Mulali Member is named after Mulali (Reedy Creek) and consists of upward coarsening cycles of shale and sandstone, with minor stromatolites at the base of the Skewthorpe Formation. The type section is the basal 36 m of the type section of the Skewthorpe Formation at Hart Spring (Figs. 34 and 35; also Table 2).

The Galawa Member is named after Galawa (Old Dip Yard) and consists of cross-bedded oolitic sandy dolomite with common stromatolites lying between the Mulali and Djigumirri Members. The type section is the interval from 36.0 m to 51.6 m above the Hart Spring Sandstone, in the type section of the Skewthorpe Formation at Hart Spring (Fig. 34).

The Djigumirri Member is named after Djigumirri (False House Roof Hill) and consists of siltstone with a lenticular horizon of stromatolite bioherms, which overlies the Galawa Member and is overlain either by the Bolgumirri Member or Pretlove Sandstone. The type section is at Hart Spring, from 51.6 m to 73.6 m above the Hart Spring Sandstone (Fig. 34).

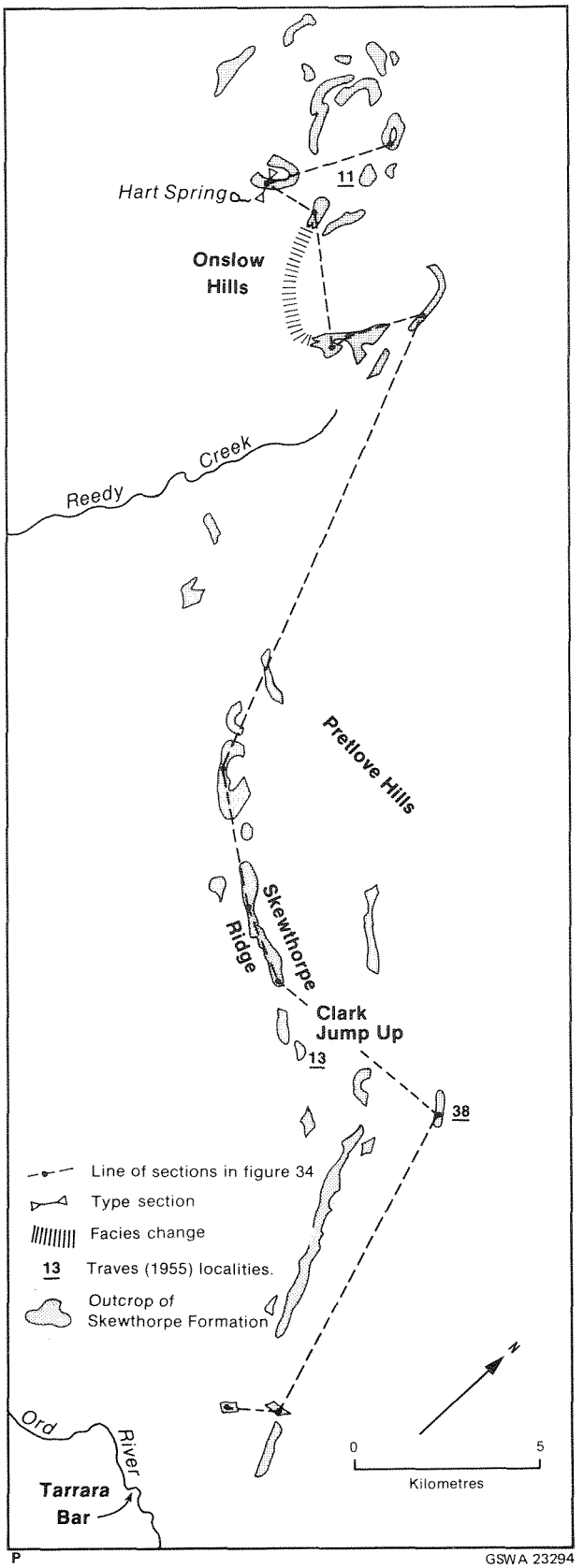

Figure 35. Distribution of outcrop of the Skewthorpe Formation between Buffalo Tank and Tarrara Bar showing the location of measured sections in Figure 34.

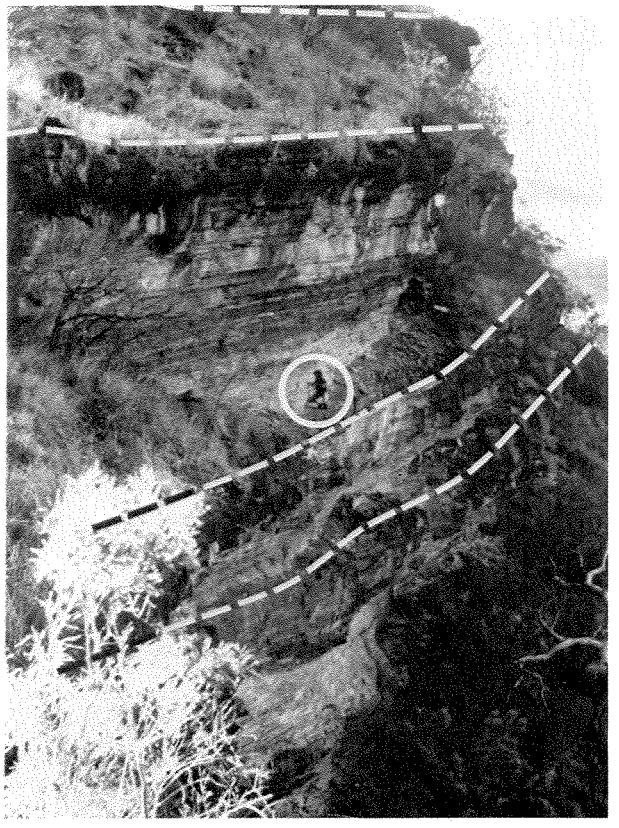

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Figure 36. Coarsening-upward cycles in the Mulali Member (Skewthorpe Formation) with the cycle tops indicated by dashed lines. This locality is part of the Hart Spring section in Figure 34. Figure (circled) for scale.

The Bolgumirri Member is named after Bolgumirri (House Roof Hill) and consists of a lenticular unit of cross-bedded oolitic and sandy dolomite at the top of the Skewthorpe Formation. The type section is the interval from 40.7 m to 84 m above the Hart Spring Sandstone, in the measured section 2 km east of Clark Jump Up (at 15°25′50″S, 128°39′10″E).

Lithology: The Skewthorpe Formation consists of cross-bedded oolitic dolomite, ripple cross-laminated and cross-bedded sandstone, and shale.

The Mulali Member consists of upward-coarsening cycles of shale and sandstone (Figs 34 and 36). Lateral continuity of some of these cycles can be demonstrated for up to 5 km. The lower parts of the cycles contain lenticular and wavy bedding, as well as flasers interbedded with laminated mudstone and siltstone. Bioturbation and syneresis cracks are particularly common near the bases of cycles. Less commonly, halite impressions preserved as casts with hopper faces (Fig. 37) are present. Sandstone in the basal part of the cycles is very fine to fine grained and ripple cross-laminated. In the middle part of the cycles, the proportion of sandstone to fine-grained lithologies increases, and bed thicknesses of sandstones increase from 1-4 cm to 4-10 cm. In the upper part of the cycles medium-grained cross-bedded sandstone beds, up to 30 cm thick, become dominant. These beds are often amalgamated, giving the impression of thick bedding. At the tops of cycles a thin bed of sandy or stromatolitic dolomite may be present. In the Onslow Hills area the uppermost cycle of the Mulali Member is capped by a distinctive stromatolite bed up to 2.5 m thick (Fig. 38). This bed persists across the Onslow Hills for a distance of 10 km along strike.

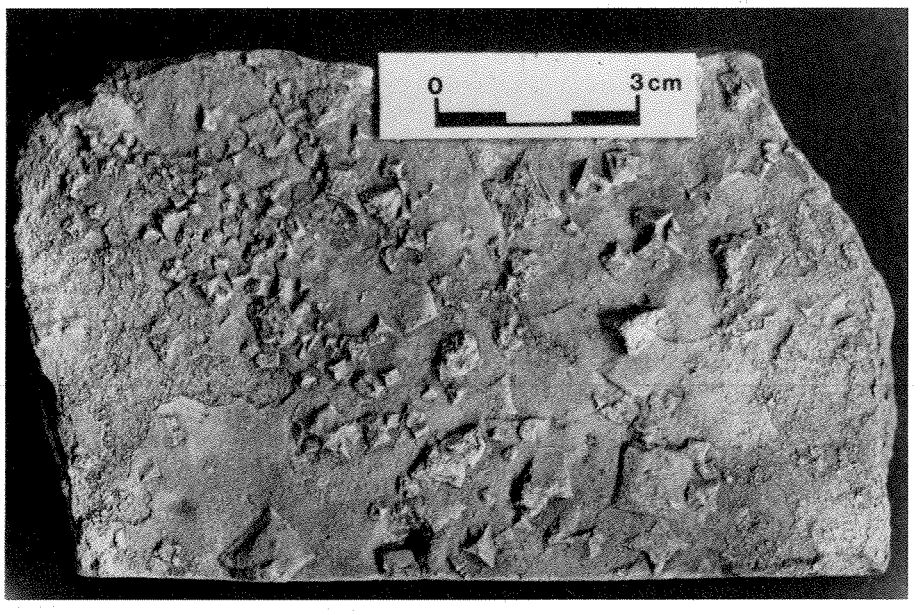

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Figure 37. Casts of halite crystals with poorly developed hoppers on the lower surface of a sandstone bed from the base of an upward-coarsening cycle in the Mulali Member (Skewthorpe Formation), 2 km east of Hart Spring.

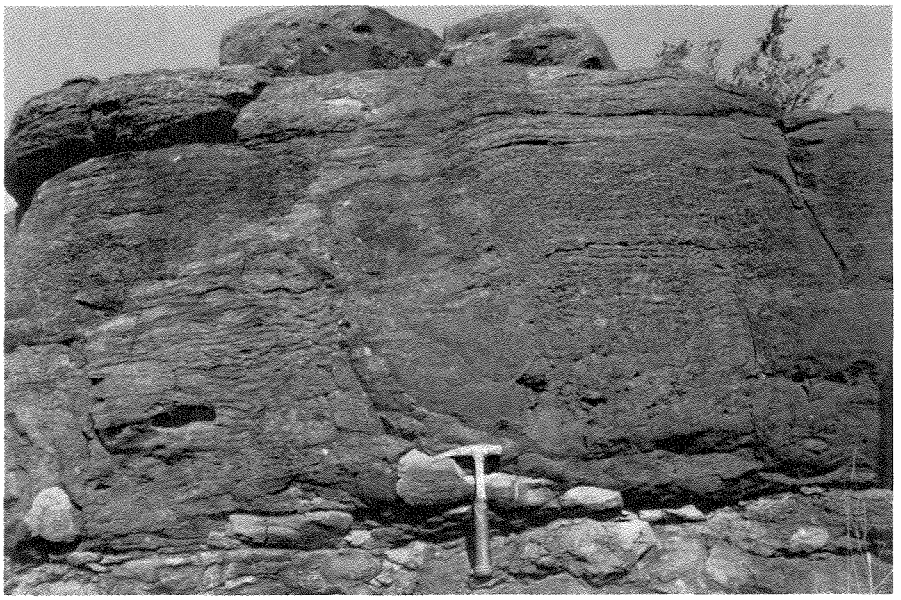

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Figure 38. ***Stromatolite marker bed at the top of the Mulali Member (Skewthorpe Formation), East Onslow Hills (south) section (Fig. 34).***

The Galawa Member consists predominantly of cross-bedded oolitic sandy dolomite with abundant stromatolites throughout (Fig. 39). Sandstone and shale interbeds are rare giving an overall massive appearance to the outcrop. Also present in this member are thin discontinuous beds, generally less than 0.5 cm thick, of dolomite with microbial laminations and sand-filled desiccation cracks (Fig. 40) associated with intraformational breccias.

The Djigumirri Member consists predominantly of laminated siltstone with subordinate, thin, ripple cross-laminated sandstone beds (showing brush marks on the lower surface) and rare lenticular cross-bedded sandy dolomite. Also present is a distinctive lenticular horizon of yellow-brown stromatolite bioherms, which generally weather out of the siltstone and occur as scree blocks.

The Bolgumirri Member consists of thin-bedded, weakly glauconitic, cross-bedded oolitic dolomite and sandy dolomite. The thinly bedded nature of this unit suggests that siltstone interbeds are present, although not observed in outcrop. Rare thin dolomite with microbial laminations and intraformational breccia are also present.

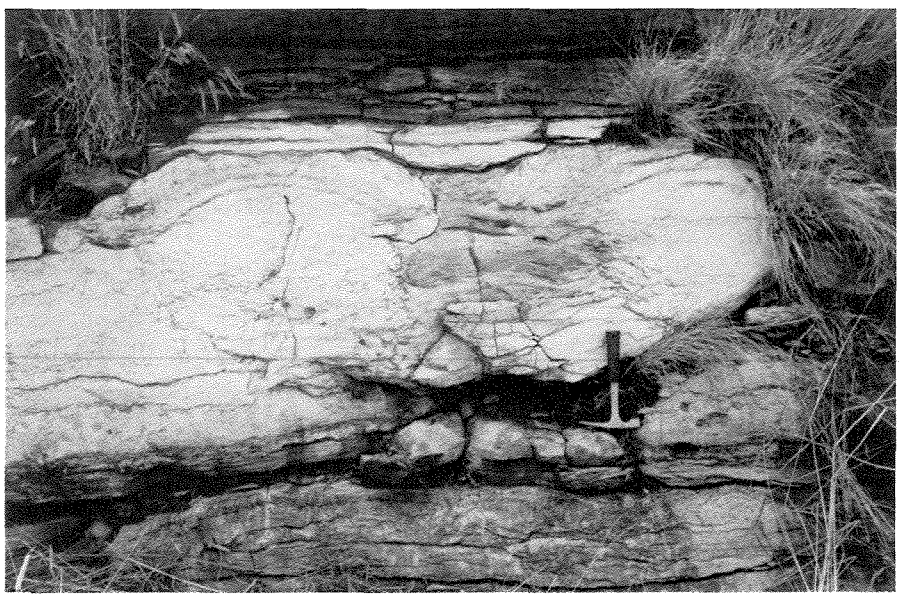

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Figure 39. Stromatolite bioherms with eroded tops in the Galawa Member (Skewthorpe Formation), Hart Spring.

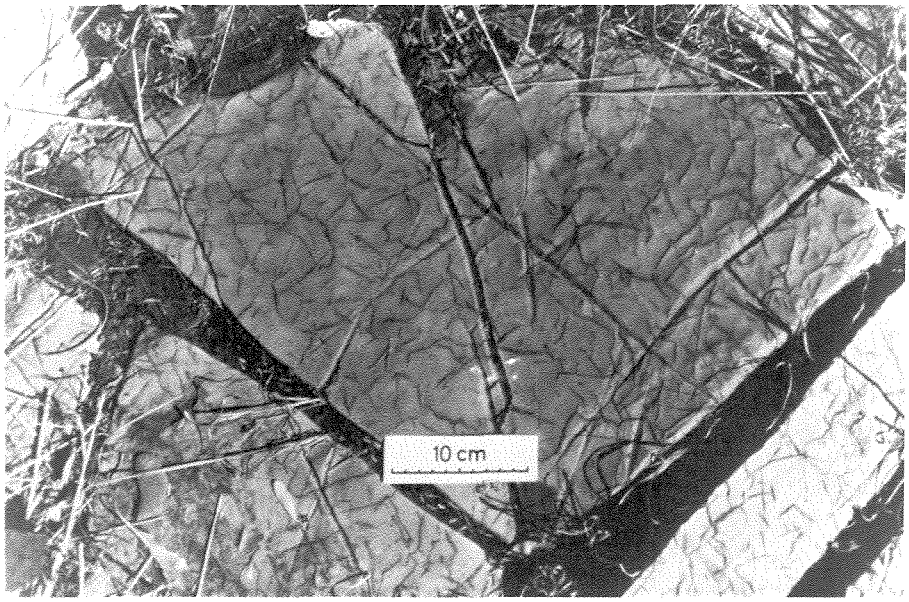

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Figure 40. Sand-filled desiccation cracks in dolomite with microbial laminations. Galawa Member (Skewthorpe Formation) near Reedy Creek.

Stratigraphic relationships: The Mulali Member of the Skewthorpe Formation conformably overlies the Hart Spring Sandstone with an abrupt contact. Similarly the upper contact with the Pretlove Sandstone is conformable with either the Djigumirri or Bolgumirri Members. Two kilometres east of Hart Spring there is an abrupt facies change, from dolomites and clastics of the lower three members of the Skewthorpe Formation into clastics of the Pretlove Formation (Fig. 41). This facies change persists for 3 km along strike to the southeast, where the carbonates of the Skewthorpe Formation abruptly reappear on the east side of Onslow Hills (Fig. 35). The distinctive stromatolite bed in the Skewthorpe Formation, shown in Figure 38, is present on both the eastern and western sides of this facies change.

Distribution and thickness: The Skewthorpe Formation outcrops as a discontinuous northwest-oriented belt in the Bonaparte Basin between Mermaid Point and Tarrara Bar (Fig. 35). Isolated

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Figure 41. Abrupt facies change from dolomite (forming dark benches on left of photograph), sandstone, and shale of the Skewthorpe Formation (Ɛ *ms*) into sandstone and shale of the Pretlove Sandstone (Ɛ *up*). The cliff below is Hart Spring Sandstone (Ɛ *mh*). The Skewthorpe Formation is 62 m thick in this section, 2 km east of Hart Spring.

outcrops are also found in the Mount Rob–Gap Point Outlier. Within the main belt of outcrop, the thickness of the formation varies from approximately 120 m at Mermaid Point to 40 m northwest of Clark Jump Up. In the Mount Rob–Gap Point Outlier the unit is approximately 20 m thick, but only the Mulali and Galawa Members are present. Of the four members only the Bolgumirri Member is lenticular and, in contrast with the underlying three members, thickens to the northeast across the strike of the outcrop belt. Where sections can be compared across the outcrop belt, the Mulali, Galawa and Djigumirri Members thin to the northeast. Within the outcrop belt the Mulali Member varies in thickness from 10 to 40 m, the Galawa Member varies from 5 to 47 m, the Djigumirri Member from 7.5 to 22 m and the Bolgumirri Member from 0 to 44 m.

Fossils and age: It was from the Skewthorpe Formation that Reeves (1949) made the first collection of Cambrian fossils in the Bonaparte Basin. The trilobites and brachiopods collected by Reeves, and subsequently by Traves (1955) and Kaulback and Veevers (1969), have so far only been identified to generic level. Öpik (1950) identified the brachiopods *Acrotreta, Obolus,* and *Lingula* and, (*in* Kaulback and Veevers, 1969), the trilobites *Peronopsis, Grandagnostus, Ptychagnostus* and *Blackwelderia* as well as several unnamed new genera. The trilobites suggest a Middle to Late Cambrian (Boomerangian to Mindyallan) age.

Stromatolites are the most conspicuous fossils in the Skewthorpe Formation but have so far received little attention, apart from the brief descriptions of Kaulback (in Kaulback and Veevers, 1969).

Depositional environment: Upward-coarsening cycles in the Mulali Member probably represent shoaling-upward sequences. A restricted intertidal to subtidal environment, such as a lagoon, is suggested by bioturbated, lenticular, wavy and flaser bedding as well as rare halite casts at the bases of cycles. Cross-bedded sandstone near the tops of cycles indicates a period of intensive transport. Intraformational breccias (occasionally associated with dolomite containing microbial laminations or stromatolites at the tops of the cycles) suggest a decrease in current activity, probably in shallow water, at the culmination of each cycle. The stromatolite marker horizon at the top of the Mulali Member, in Onslow Hills, indicates a relatively widespread, stable, quiet environment, prior to the influx of the coarse-bedded oolitic sandy carbonate of the Galawa Member.

In the Galawa Member, the association of intraformational breccias and desiccation cracks (developed in the carbonate with microbial laminations) suggest deposition in an environment which was at least partially subaerially exposed. The cross-bedded oolitic sandy carbonate lithology of the Galawa Member suggests that this environment was a carbonate-sand bank.

Laminae in the siltstones of the Djigumirri Member indicate deposition from suspension in a quiet environment, while rare trace fossils and the presence of stromatolite bioherms indicate a marine environment. The protected subtidal environment proposed for this member is also suggested by its stratigraphic position between a carbonate-sand bank (the Galawa Member) and a subtidal ooid shoal (the Bolgumirri Member).

In the Bolgumirri Member the ubiquitous cross-bedding and oolitic carbonate, as well as the lack of structures indicating subaerial exposure, are interpreted to indicate that this unit was deposited as a subtidal ooid shoal.

The depositional model proposed for the Skewthorpe Formation is summarized in Figure 42. Upward-shoaling cycles at the base of unit (Mulali Member) possibly represent flood-tidal deltas deposited in a lagoonal environment. The succeeding cross-bedded oolitic sandy carbonate (Galawa Member) was deposited as a stable carbonate-sand bank. Stromatolites proliferated on this bank which protected a lagoon that developed on its southwestern side. The abrupt facies change from Skewthorpe Formation to Pretlove Sandstone east of Hart Spring (Figs 35 and 41) is speculated to represent a wide clastic-filled channel cutting through the carbonate-sand bank as shown in Figure 42. The succeeding silts (Djigumirri Member) and cross-bedded oolitic carbonate (Bolgamirri Member) are probably subtidal.

PRETLOVE SANDSTONE

Definition: Traves (1955) gave the name Pretlove Sandstone to "the sandstone that crops out in the Pretlove Hills". The subsequent investigation of Veevers and Roberts (1968) revealed that most of the Pretlove Hills consisted of Devonian sandstone now assigned to the Cockatoo Group. Kaulback and Veevers (1969) restricted the Pretlove Sandstone to the "sandstone that conformably overlies the Skewthorpe Formation and is conformably overlain by the Clark Sandstone" with their section 245, as the type section, 6.4 km southeast of Clark Jump Up. This section runs from 15°29′20″E, 128°39′35″S (base) to 15°29′20″E, 128°39′40″S (top).

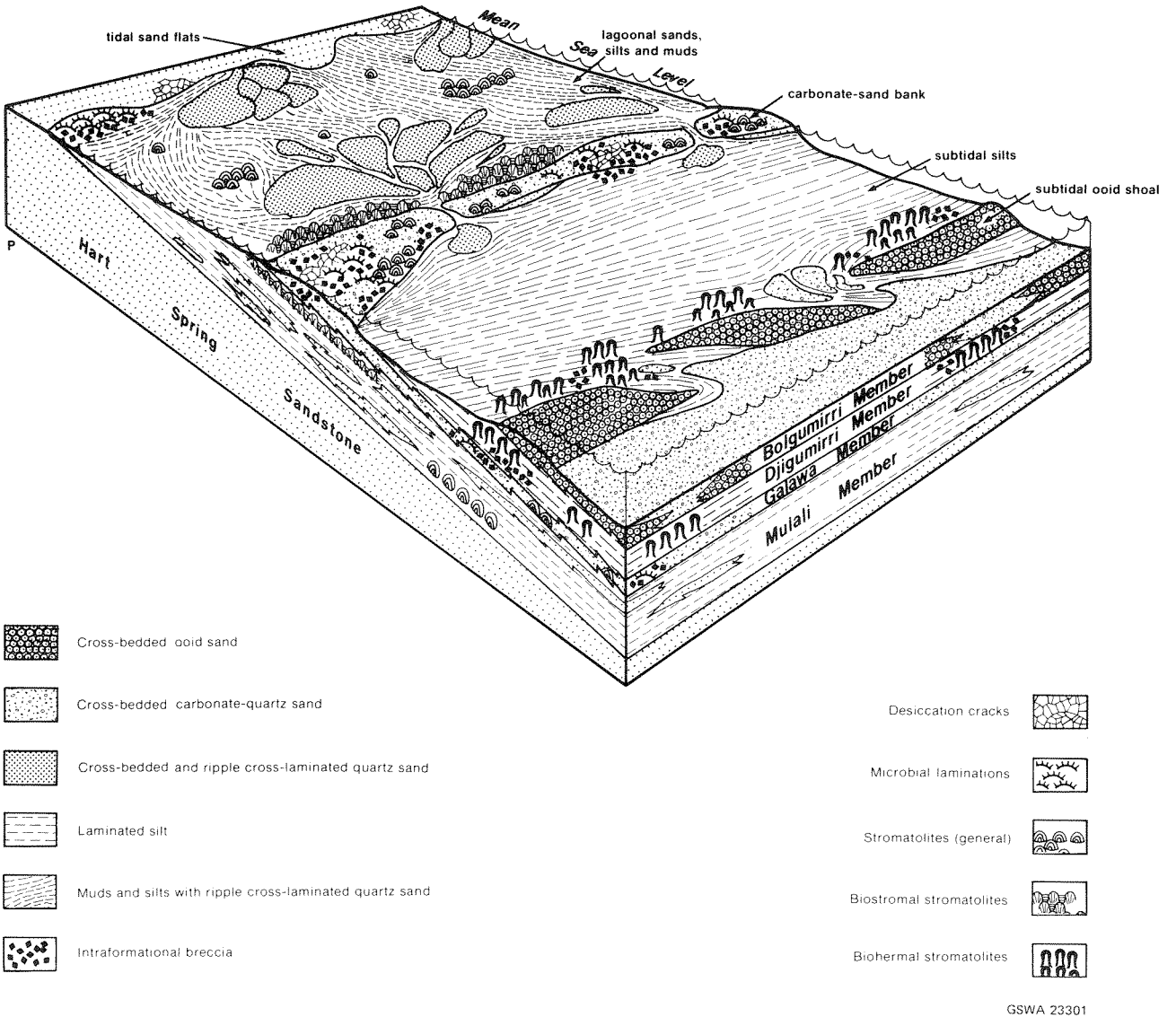

Figure 42. Depositional model for the Skewthorpe Formation.

The presence of thinly bedded and flaggy, fine- to medium-grained ripple cross-laminated quartz sandstone distinguishes the Pretlove Sandstone from the overlying Clark Sandstone. There is some uncertainty as to the position of the Pretlove/Clark Sandstone contact as defined by Kaulback and Veevers (1969) at Mount Rob since that section does not possess the flaggy lithology here considered diagnostic of the Pretlove Formation (Fig. 29). Consequently there is doubt as to whether some fossils identified by Öpik (*in* Kaulback and Veevers, 1969) are from the Pretlove or Clark Sandstones. However, thicknesses here determined for the Pretlove Sandstone are close to those of Kaulback and Veevers, (1969) suggesting that it is only in the Mount Rob–Gap Point Outlier that there is a substantial difference between Kaulback and Veevers' (1969) definition of this unit and that used here.

Lithology: The Pretlove Sandstone consists predominantly of thin-bedded, fine- to medium-grained, ripple cross-laminated, quartz sandstone with lesser thin-bedded, parallel-laminated and cross-bedded sandstone. Shale interbeds are rarely exposed, but are inferred to be common from the flaggy nature of sandstone beds and the abundance of syneresis cracks preserved on the base of sandstone beds (Fig. 43). Generally thinly bedded lithologies form scree slopes, with outcrop *in situ* being particularly rare. Brown to red, thick, cross-bedded, trilobite-rich sandstone horizons (similar to the Clark Sandstone) are interbedded with the thinly bedded lithologies, especially near the top of the formation.

Stratigraphic relationships: In most sections the Pretlove Sandstone conformably overlies the Skewthorpe Formation and is conformably

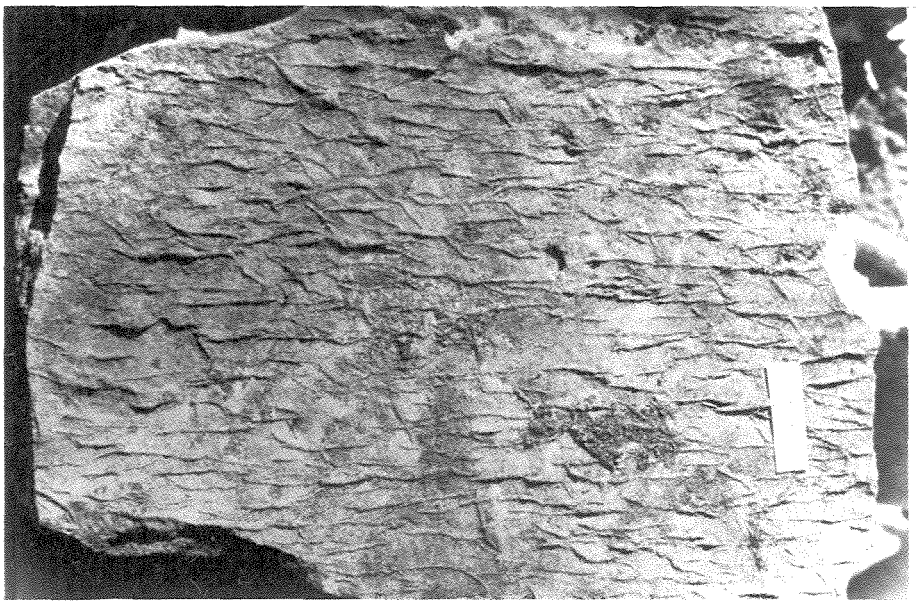

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Figure 43. Cast of oriented or 'ribbon' non-orthogonal syneresis cracks preserved on the base of a ripple cross-laminated sandstone bed. Pretlove Sandstone, East Onslow Hills section (Fig. 29).

overlain by the Clark Sandstone. In the Onslow Hills the unit conformably overlies the Hart Spring Sandstone, with a rapid lateral facies change into the Skewthorpe Formation evident 2 km east of Hart Spring (Fig. 41) and at the eastern side of Onslow Hills. In the Mount Rob–Gap Point Outlier the Pretlove Sandstone is not present, presumably due to a facies change with the Clark Sandstone. Fossil evidence suggests that this upper contact is diachronous (Öpik, *in* Kaulback and Veevers, 1969).

Distribution and thickness: The Pretlove Sandstone crops out discontinuously within the main belt of outcrop of the Carlton Group, between Mermaid Point and Tarrara Bar in the Bonaparte Basin. The unit is not present in the outliers to the south. The formation varies in thickness from 24 to 90 m where it overlies the Skewthorpe Formation, and is 75 m thick in the type section (Fig. 29). In the Onslow Hills a thickness of 125 m is estimated where the Skewthorpe Formation is absent.

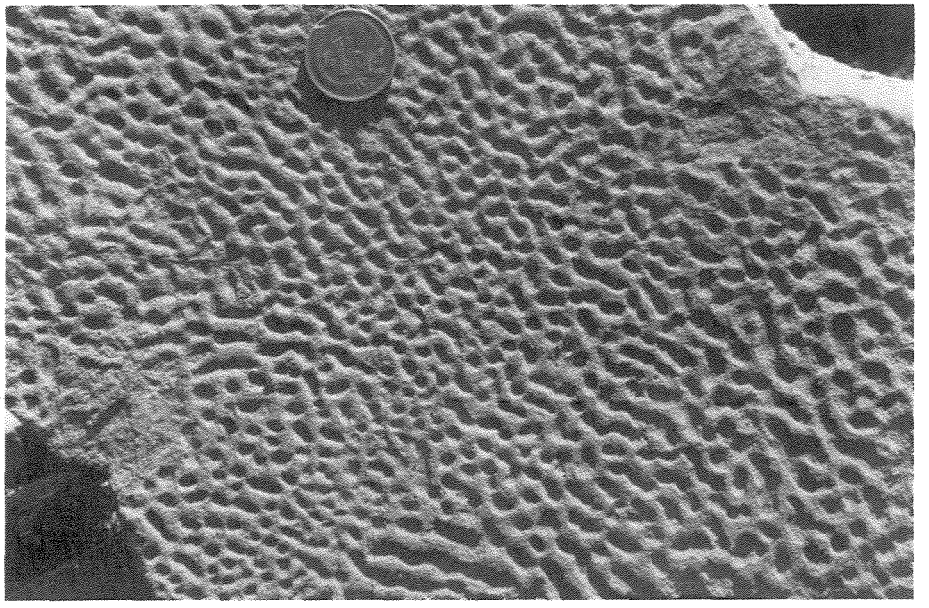

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Figure 44. Wrinkle marks, formed at the interface of water and cohesive sediment by wind blowing over a thin film of water, indicating intermittent emergence. Pretlove Sandstone, 8 km southwest of Clark Jump Up. Coin is 1.7 cm in diameter.

Fossils and age: The Pretlove Sandstone is poorly fossiliferous, containing occasional gastropods, phosphatized brachiopods and trilobites, including *Crepicephalus*, (Traves, 1955). The late Cambrian age and diachronous nature of the Pretlove Sandstone are determined largely from ages of the enclosing formations.

Depositional environment: The presence of desiccation cracks, interference and flat-topped ripples, wrinkle marks (Fig. 44) and trace fossils in the thinly bedded sandstone of the Pretlove Sandstone indicate an intertidal to shallow subtidal environment. Interbedded, cross-bedded, trilobitic sandstone was deposited as sinuous dunes probably in a shallow subtidal environment.

CLARK SANDSTONE

Definition: Traves (1955) gave the name Clark Sandstone "to the sandstone which crops out on the eastern side of the fault at Clark Jump Up." Kaulback and Veevers (1969) named this locality as the type section even though it "is isolated by faults and by sand". A complete section was located 6 km to the southeast (Kaulback and Veevers' section 245). This latter section (shown as Clark Jump Up in Figure 29) is here designated as a reference section for the unit.

Lithology: The Clark Sandstone consists of fossiliferous, medium-grained, poorly-sorted, quartz sandstone with feldspar, glauconite, chert and tourmaline. Sand grains are usually coated with hematite giving the unit a dark-red to brown colour. In outcrop the unit consists of thin- to medium-bedded, festoon cross-bedded sandstone with rare thin horizons of bioturbated, ripple cross-laminated sandstone.

Stratigraphic relationships: The Clark Sandstone conformably overlies the Pretlove Sandstone north of the Ord River. In the Mount Rob–Gap Point Outlier the Clark Sandstone conformably overlies the Skewthorpe Formation and is deduced to be, in part, laterally equivalent to the Pretlove Sandstone. The Clark Sandstone is conformably overlain by the Pander Greensand in the Clark Jump Up area; elsewhere the unit is either disconformably overlain by, or faulted against, the Devonian Cockatoo Group.

Distribution and thickness: The Clark Sandstone has a patchy distribution between Mermaid Point and Tarrara Bar. The formation is also present east of Jeremiah Hills in Weaber Plain and in the Mount Rob–Gap Point Outlier. The Clark Sandstone is 220 m thick in the Clark Jump Up area and 320 m at Mount Rob (Fig. 29), the only areas with complete sections through the unit.

Fossils and age: The Clark Sandstone is highly fossiliferous, containing abundant trilobites, brachiopods and gastropods. Öpik (*in* Kaulback and Veevers, 1969) indentified a sequence of five faunal divisions based on the trilobite faunas which range in age throughout the Late Cambrian (Idamean to Payntonian). From these trilobite faunas Kaulback and Veevers (1969, Fig. 9) showed that the base of the Clark Sandstone is diachronous, with the unit becoming younger to the southeast and south.

Depositional environment: The highly fossiliferous glauconitic nature of the Clark Sandstone suggests deposition on an open-marine shelf. Palaeocurrents (determined from festoon cross-beds) are predominantly to the north-northeast (Fig. 45) and are interpreted as indicating the movement of sinuous megaripples by offshore-directed currents.

PANDER GREENSAND

Definition: Noakes and others (1952) referred to the "fossiliferous glauconitic sandstones of Lower Ordovician age" at Pander Ridge as the "Pander Sandstone". Traves (1955) amended this name to the Pander Greensand. Traves' locality 8 (Veevers and Roberts 1968, section 233) at Pander Ridge is regarded as the type section (Jones, 1971; Playford and others, 1975). The most complete section, however, is an isolated hill located 1 km northeast of Clark Jump Up: the basal 15 m of this section is

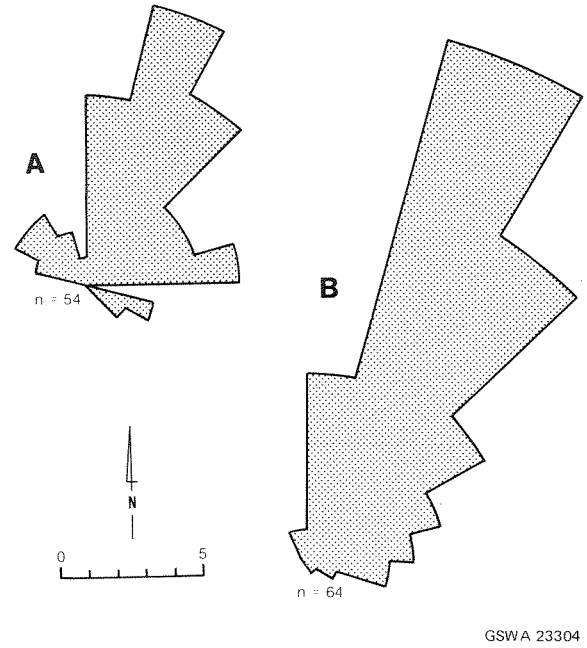


Figure 45. Palaeocurrent directions based on festoon axes from (A) Clark Sandstone and (B) Pander Greensand, both in the Clark Jump Up area. Scale shows number of readings per 15° segment.

latest Cambrian in age (Jones, 1971). While Kaulback and Veevers (1968) suggested that the basal 15 m "may belong to the Clark Sandstone", it cannot be distinguished lithologically from the Ordovician part of the section, so it is here included in the Pander Greensand.

Lithology: The Pander Greensand consists of grey to green, medium-grained, glauconitic, quartz sandstone. The glauconite is present mainly as detrital grains, also as an interstitial mineral. In outcrop the unit consists of festoon cross-beds with minor parallel-bedded horizons, along which fragments of phosphatic shells are often concentrated.

Stratigraphic relationships: The Pander Greensand is deduced to conformably overlie the Clark Sandstone, using the evidence from its latest Cambrian to earliest Ordovician trilobite and conodont faunas. All outcrops of the unit occur as isolated low hills and the contacts with the enclosing units are not exposed. The Pander Greensand is the youngest of the Lower Palaeozoic units exposed in the Bonaparte Basin. A disconformity spanning the Middle Ordovician to Middle Devonian is present between the Pander Greensand and overlying Cockatoo Group.

Distribution and thickness: The Pander Greensand forms five isolated hills, east of the track near Clark Jump Up, and low outcrops 10 km east-southeast of Mermaid Point. The unit varies in thickness in the Clark Jump Up area from 40 m at Pander Ridge to 120 m located 1 km northeast of Clark Jump Up.

Fossils and age: The Pander Greensand contains a diverse fauna of conodonts, trilobites, brachiopods, and gastropods, together with rare cystoids and eocrinoids. The Early Ordovician age of the unit was first determined by Öpik (1950) who recorded the presence of the conodont genera cf. *Drepandus* and cf. *Acontiodus*. Later, Öpik (*in* Kaulback and Veevers, 1969) reported Richardsonellidae, Leiostegiidae and protopliomerid tribolites from the unit, indicating a late Tremadocian to early Arenigian age. Jones' (1971) report on the conodont fauna of the Pander Greensand indicates a latest Payntonian (Late Cambrian) to early Arenigian age of the unit.

Depositional environment: The strongly glauconitic nature of the Pander Greensand indicates deposition in a marine environment of moderate water depths. Palaeocurrents are predominantly to the north-northeast (Fig. 45), a direction consistent with that in Cambrian units. This suggests little change of the palaeoslope in the early Palaeozoic. Interbeds of parallel-laminated sandstone with shell fragments may represent deposition as a result of storm activity.

CHAPTER 3

Frasnian of the Bonaparte and Ord Basins

INTRODUCTION

The Frasnian sequences of the Bonaparte and Ord Basins are referred to as the Cockatoo and Mahony Groups, respectively. Three previous workers examined the two groups. Jack (1906), in his interpretation, included much of the Proterozoic sequence south of Wyndham with the Devonian sequence. Wade (1924) made only a small contribution, noting little more than the similarity of the section at Matheson Ridge with that at Mount Buchanan and Glass Hill. While Traves (1955) briefly examined the "Cockatoo Sandstone" his observations on the Devonian part of his "Elder Sandstone" in the Ord Basin are mostly from Wade (1924). Much of the latter formation is assigned a Cambrian age (Mory and Beere, 1985). The two groups are described together, here, as they not only show striking resemblances in their outcrop characteristics and lithologies, but they also have facies and facies associations in common.

COCKATOO GROUP

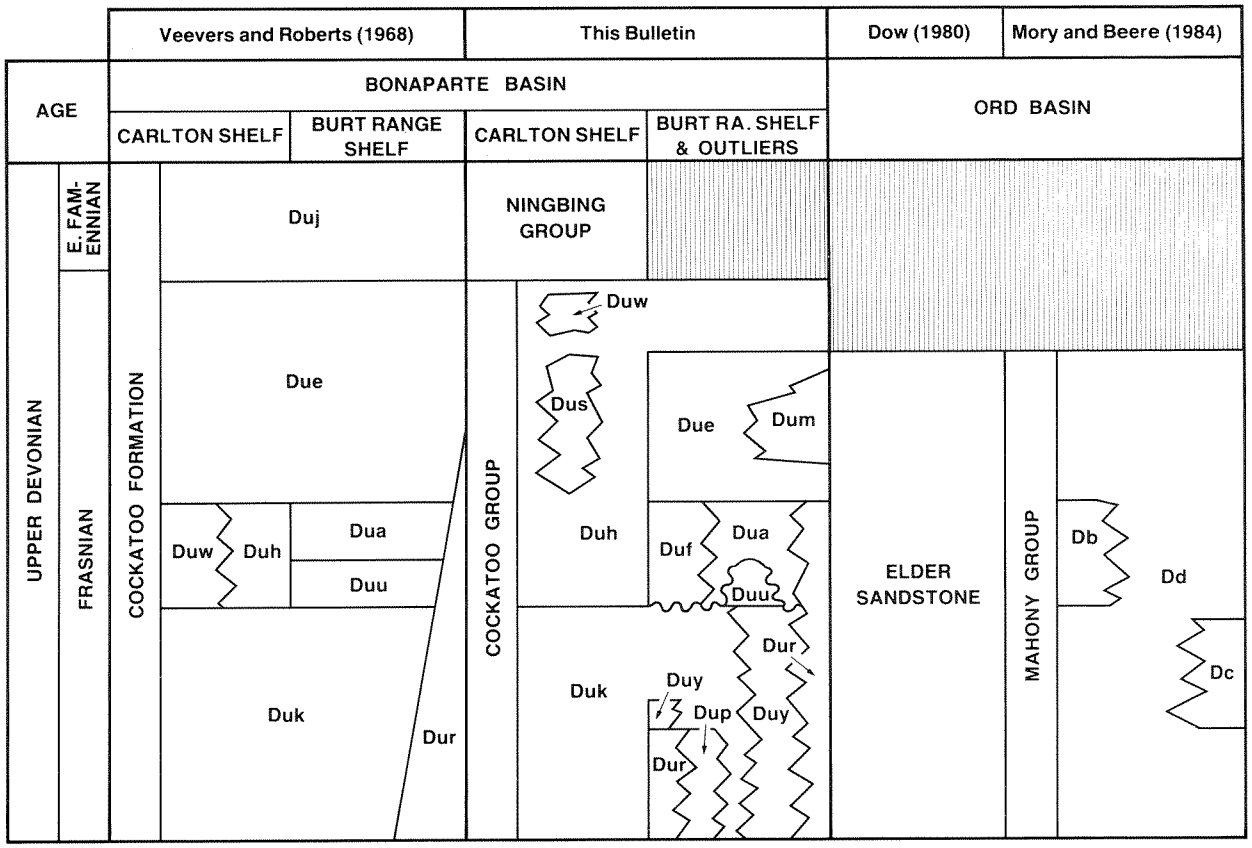
The Cockatoo Group consists of ten formations in the Bonaparte Basin and its outliers (Fig. 46). The group was first termed "Cockatoo Series" and mapped in the Burt Range Shelf and part of the Carlton Shelf by Matheson and Teichert (1948); further mapping was carried out by Reeves (1949). Traves (1955) mapped the Dillon Spring Outlier and recorded several fossil occurrences. Veevers and Roberts (1968) recognized the remaining outcrop areas and subdivided the Cockatoo "Formation" into eight members (Fig. 46). Their work forms the basis of the present study, and several changes have been made. A brief account of these changes was presented by Beere and Mory (1986).

The Cockatoo Group overlies Proterozoic, Cambrian, and Ordovician rocks with angular unconformity. The Ningbing Group overlies the Cockatoo Group, conformably on the Carlton Shelf and disconformably on the Burt Range Shelf. In the Ragged Range, Dillon Spring and Mount Rob–Gap Point Outliers the Cockatoo Group is the youngest Palaeozoic unit exposed.

The lateral and vertical stratigraphic relationships of the twelve units (including two members) within the Cockatoo Group are complex and are summarized in Figure 47. Many units are lithologically similar, and two marker sequences of red pebbly sediments provide some control on correlations. These marker sequences have basal unconformities, and form the lower part of informal lower and upper subdivisions of the Cockatoo Group.

A regional unconformity separates the lower Cockatoo Group from Proterozoic, Cambrian, and Ordovician rocks. The lower marker sequence is formed by the Ragged Range Conglomerate and its lateral equivalent the Steeple Peak Sandstone. Angular unconformities occur within the Ragged Range Conglomerate at Ragged Range. This conglomerate is also laterally equivalent to the Cyril Sandstone. Both the Cyril and Steeple Peak Sandstones interfinger with the Kellys Knob Sandstone. This latter unit appears to be a blanket deposit on both the Carlton and Burt Range Shelves, although it does not occur in eastern parts of the Burt Range Shelf. The uppermost part of the lower Cockatoo Group locally consists of Kununurra Formation.

In the upper Cockatoo Group on the Burt Range Shelf and in the outliers, the marker sequence consists of Ragged Range Conglomerate, Galloping Creek Formation, and the laterally equivalent Abney Sandstone. In central Ragged Range the Galloping Creek Formation overlies the Kellys Knob Sandstone with angular unconformity. In the Kununurra area the Kununurra Formation is absent, and Abney Sandstone disconformably overlies Kellys Knob Sandstone. Elsewhere the lower contact with Kununurra Formation is conformable. Angular unconformities probably occur within the Galloping Creek Formation. The marker sequence is covered by the Cecil Sandstone, which contains a lens of Maudoobar Sandstone; this in turn is overlain by the Hargreaves Formation. On the Carlton Shelf,



Db	Boll Conglomerate	Duf	Galloping Creek Formation	Dup	Steeple Peak Sandstone
Dc	Purralili Sandstone	Duh	Hargreaves Formation	Dur	Ragged Range Conglomerate
Dd	Glass Hill Sandstone	Duj	Jeremian Member	Dus	Siggins Spring Member
Dua	Abney Sandstone	Duk	Kelly's Knob Sandstone	Duu	Kununurra Formation
Due	Cecil Sandstone	Dum	Maudoobar Sandstone	Duw	Westwood Member
				Duy	Cyril Sandstone

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Figure 46. Stratigraphy of the Cockatoo and Mahony Groups showing the relationship of the present nomenclature with that of the most recent previous workers.

red sediments are absent and the base of the upper Cockatoo Group is taken as the top of the Kellys Knob Sandstone. The Hargreaves Formation is probably equivalent to all the units on the Burt Range Shelf and it includes both the Siggins Spring and Westward Members. The Siggins Spring Member is stratigraphically equivalent to the Cecil Sandstone, and the Westwood Member probably occurs in the uppermost part of the Cockatoo Group.

The group ranges in thickness from 1620 m (Burt Range Shelf) to 2730 m (central Ragged Range Outlier, Fig. 47). The most complete unfaulted section occurs at Matheson Ridge, where the basal 900 m is well exposed and the remaining 720 m is poorly exposed. Extensive strike faulting on the Carlton Shelf precludes a thickness measurement and the thickness is assumed to be similar to that on the Burt Range Shelf. The Ragged Range section is also poorly known and is a composite thickness estimated from several fault blocks. In the lower Cockatoo Group the thickest sections occur in the central Ragged Range (730 m) and Matheson Ridge areas (550 m). Thinning occurs to the north and west on to the Carlton Shelf (Hargreaves Hills, about 300 m). The upper Cockatoo Group is 2000 m and 1600 m thick in central and southern Ragged Range, respectively. Thinning occurs to the north and northeast on the Carlton and Burt Range Shelves (1300 m and 1050 m, respectively).

Fossils occur sporadically throughout the group and include bivalves, brachiopods, trace fossils, and wood. The group is dated principally by the Westwood Member in which there is a diverse and abundant fauna of Frasnian age (Veevers and Roberts, 1968). Other units within this group with little or no macrofauna can only be assigned a

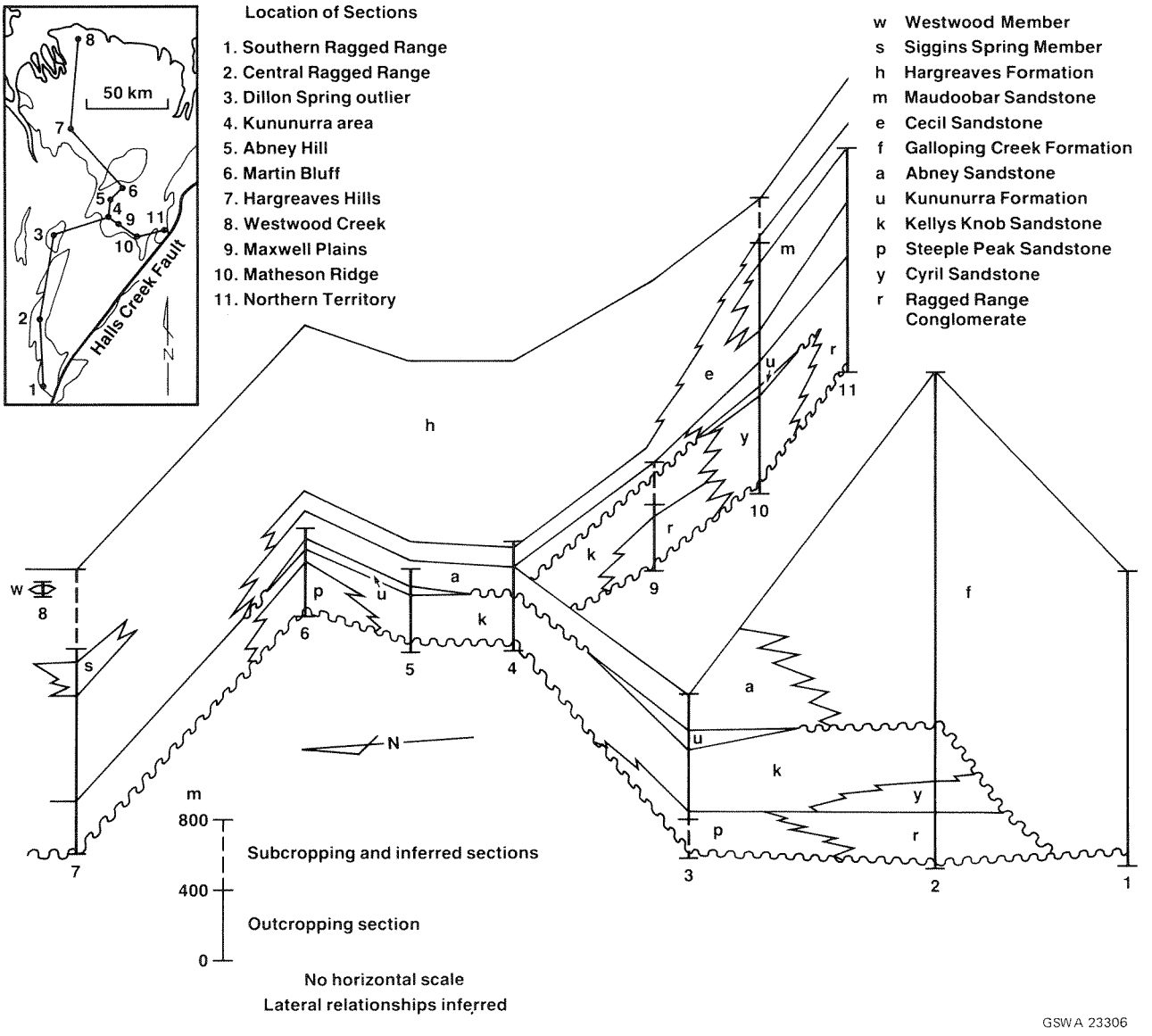

Figure 47. Cockatoo Group stratigraphic relationships, distribution, and thickness.

general Frasnian age from their stratigraphic position within the group.

For ease of reference and comparison with the coeval Mahony Group in the Ord Basin, the lower and upper stratigraphic divisions of the Cockatoo Group are referred to as lower and upper Frasnian units, respectively.

RAGGED RANGE CONGLOMERATE

Definition: The Ragged Range Conglomerate (Traves, 1955) consists of red-brown conglomerate, pebbly quartz sandstone, and minor quartz sandstone. Veevers and Roberts (1968) designated the type section at Conglomerate Hill in Ragged Range, 16 km north of Glenhill homestead (16°24'S, 128°21'E), marking the base of the unit as the lowest conglomerate. However, the underlying friable quartz sandstone, previously assigned to the "Blatchford Formation", is now included in the Ragged Range Conglomerate.

Lithology: The unit consists of conglomerate, pebbly sandstone, and sandstone-dominated sequences. The conglomeratic sequence consists of extremely thick conglomerate with minor sandstone beds and lenses. The pebbly sandstone sequence consists of thick intercalations of the major lithologies. The sandstone sequence lacks coarser lithologies.

Conglomerate is polymodal and clast supported or, more rarely, sand supported. Clasts consist of rounded to well-rounded quartzite, up to 1.2 m diameter in the conglomerate sequences or 0.4 m in the pebby sandstone sequence. Locally, angular clasts of Proterozoic indurated shale and siltstone are common. Massive bedding is dominant with rare trough cross-bedding and parallel

bedding. Pebbly sandstone is moderately sorted, fine to coarse grained, and trough or planar cross-bedded. Sandstone is a very fine- to medium-grained, moderately to well- sorted, quartz arenite. It may contain scattered granules and pebbles, and it may grade into siltstone. Near granitic basement in southern Ragged Range the sandstone is arkosic. Lamination and low-angle cross-bedding are dominant, planar cross-bedding is locally common, and trough cross-bedding and ripple cross-lamination are minor.

Stratigraphic relationships: The Ragged Range Conglomerate overlies older units with an angular unconformity. In northern Ragged Range and in the type section, the Ragged Range Conglomerate overlies the Tarrara Formation, to the south it overlies the Antrim Plateau Volcanics and in the Cockatoo Spring–southeast Matheson Ridge area it overlies Proterozoic volcanics, foliated sandstone, and schist. Local intraformational angular unconformities occur along reactivated basement faults in Ragged Range. At locality 2096 (Fig. 58), folds occur in overlying rocks, indicating continued fault movements. The Ragged Range Conglomerate is conformably overlain by the Cyril Sandstone in northern Ragged Range, and the Kellys Knob Sandstone at Maxwell Plains.

A tongue of upper Frasnian Ragged Range Conglomerate extends from the Northern Territory into Matheson Ridge, so that the unit conformably overlies the Kununurra Formation and is conformably overlain by the Cecil Sandstone (Fig. 46).

Distribution and thickness: The Ragged Range Conglomerate occurs in the Ragged Range and in the southern and eastern parts of the Burt Range Shelf. The type section is about 290 m thick, and the thickest section of about 600 m is east of the Cockatoo Fault.

Fossils: Fossils are rare in the northern Ragged Range, consisting of indeterminate bivalves and gastropods at the base of the unit, and bivalves at the top (Veevers and Roberts, 1968). Small crinoid columnals occur in concretions in silty sandstone near the base of the type section.

STEEPLE PEAK SANDSTONE

Definition: The Steeple Peak Sandstone (Beere and Mory, 1986) consists of red, feldspathic sandstone, quartz sandstone, and minor conglomerate. The name is derived from Steeple Peak, 21 km north-northeast of Kununurra, and the type section is at this locality (base 15°36′20″S, 128°49′00″E; top 15°37′00″S, 128°49′20″E). Veevers and Roberts (1968) mapped the type area as Ragged Range Conglomerate, although lithologically it is similar to the Abney Sandstone, differing mainly in its stratigraphic position in the lower Cockatoo Group.

Lithology: In the type section the sandstone is fine to medium grained, and well sorted; adjacent to conglomerate it is slightly pebbly. Basal sands commonly contain basalt fragments reworked from the underlying Antrim Plateau Volcanics. Laminated to very thin parallel bedding is dominant, with minor thin to medium trough and planar cross-bedding, rare low-angle cross-bedding, and interference ripples. Parting lineation is common in the laminated sandstone. Lenticular conglomerate up to 4 m thick occurs near the base of the type section. The conglomerate is clast supported, bimodal, massive, planar cross-bedded, parallel bedded, and has a sharp discordant upper contact with the sandstone. Clasts consist of pebbles, cobbles, and minor boulders (up to 1 m) of quartzite, basalt, granitoid, and siltstone; the clasts may be imbricated. At Dillon Spring only the upper part of the formation is exposed. It is similar to the type section, but contains only scattered coarse sand, granules, and thin pebble lags. Wavy and flaser bedding and bioturbation are also present.

Stratigraphic relationships: The Steeple Peak Sandstone unconformably overlies both the Antrim Plateau Volcanics at the type section and the Carlton Group at Dillon Spring. In both sections it is conformably and gradationally overlain by the Kellys Knob Sandstone.

Distribution and thickness: The Steeple Peak Sandstone is a lenticular body, occurring around Steeple Peak and Dillon Spring. The type section, at an estimated 260 m, is the thickest known. Rapid thinning occurs over 8 km to the east, and the unit disappears to the south. The formation is 200 m thick at Dillon Spring.

Fossils: Bivalves occur immediately above the conglomerate at Steeple Peak (Veevers and Roberts, 1968) and trace fossils occur at Dillon Spring.

CYRIL SANDSTONE

Definition: The Cyril Sandstone (Beere and Mory, 1986) consists of white, grey, and red lithologies, which include pebbly sandstone, quartz sandstone, minor conglomerate, and rare siltstone. The name is derived from Mount Cyril, 1 km east of Kununurra. The type section is on the southern side of central Matheson Ridge (base 15°52′50″S,

128°53'10"E; top 15°52'00"S, 128°53'50"E). This section was mapped as Kellys Knob Sandstone by Veevers and Roberts (1968). Lithologically it is very similar to the Cecil Sandstone but lies at a lower stratigraphic position.

Lithology: Pebbly sandstone and quartz sandstone are fine to medium grained and moderately to well sorted. Clasts consist mainly of quartzite pebbles and cobbles with rare siltstone intraclasts. Thin to medium trough cross-bedding is dominant, with lesser planar cross-bedding and parallel bedding; low-angle cross-bedding and ripples are minor. Conglomerate is clast- and matrix-supported, occurring in medium to very thick beds and thin lenses. It becomes less common towards the top of this unit. Clasts consist mainly of subangular to subrounded quartzite and rare intraformational siltstone up to 20 cm in diameter. Parallel bedding and trough cross-bedding are dominant. Siltstone occurs in thick beds or lenses and may be laminated or rippled. At northern Ragged Range the Cyril Sandstone is less conglomeratic than in the type area.

Stratigraphic relationships: In the type section the unit unconformably overlies Antrim Plateau Volcanics, and to the southeast it overlies Proterozoic sediments with angular unconformity. It is conformably overlain by the Kununurra Formation. At Ragged Range it lies conformably between the Ragged Range Conglomerate (below) and the Kellys Knob Sandstone (above).

Distribution and thickness: The Cyril Sandstone is restricted to around Matheson Ridge and Ragged Range, where thicknesses are estimated to be 490 m and 180 m, respectively.

Fossils: Trace fossils occur rarely in siltstones in the type section.

KELLYS KNOB SANDSTONE

Definition: The Kellys Knob Sandstone (Veevers and Roberts, 1968, amended by Beere and Mory, 1986) is a unit of uniform sandstone with rare shale. The type section is 1 km east of Kellys Knob (base 15°46'00"S, 128°44'50"E; top 15°45'20"S, 128°45'30"E).

Lithology: The sandstone is a homogeneous, fine- to medium-grained, well- to very well-sorted, quartz arenite. Well-rounded frosted grains are common. Coarse sand, granules, and pebbles are rare. Medium to very thick planar cross-bedding is dominant, with minor medium to thick parallel bedding, and low-angle cross-bedding. Laminated foresets are characteristic. Deformed bedding is common and locally abundant around Kununurra. Thick shales on the Carlton Shelf may be laminated.

Stratigraphic relationships: The base is not exposed in the type section; however, 1 km to the west, the Kellys Knob Sandstone unconformably overlies the Antrim Plateau Volcanics. Elsewhere it conformably overlies, and is probably a lateral equivalent of the Steeple Peak Sandstone, Cyril Sandstone, and Ragged Range Conglomerate. The unit is disconformably overlain elsewhere by the Abney Sandstone in the type section, and conformably overlain by the Kununurra and Hargreaves Formations. In central Ragged Range it is overlain with probable angular unconformity by the Galloping Creek Formation.

Distribution and thickness: The Kellys Knob Sandstone is a tabular unit about 300 m thick, occurring on the Carlton and Burt Range Shelves, and in the Dillon Spring and Ragged Range Outliers. The type section is 280 m thick. The thickest section is 350 m at Dillon Spring, and the thinnest is 70 m at Martin Bluff.

Fossils: There are rare trace fossils at Elephant Hill.

KUNUNURRA FORMATION

Definition: The Kununurra Formation (Veevers and Roberts, 1968, amended by Beere and Mory, 1986) consists of varicoloured quartz sandstone, with minor dolomitic sandstone, dolomite, and shale. The type section is 11 km north-northeast of Kununurra (base 15°40'52"S, 128°46'20"E; top 15°41'10"S, 128°46'40"E).

Lithology: The sandstone and dolomitic sandstone are very fine to fine grained, well to very well sorted, slightly glauconitic and micaceous. The sandstone has a flaggy outcrop, in blocks up to 0.3 m thick, indicating interbedding with shale or siltstone. Blocks are thinnest in the lower 40 m of the type section. Major structures are parallel bedding and lamination, with minor ripples. The dolomitic sandstone and dolomite occur mainly around Kununurra as thick (0.5 to 4 m) beds or thinner interbeds with sandstone and shale. Thin to medium parallel bedding is dominant, with minor massive bedding, and rare lamination. Laminated shale occurs in beds, 3 – 5 m thick, and between sandstone flags.

Stratigraphic relationships: The Kununurra Formation lies conformably between the Kellys Knob Sandstone (below) and the Abney Sandstone (above). In the type section the lower contact is not exposed, and the upper contact is gradational.

Distribution and thickness: The Kununurra Formation occurs only at Dillon Spring and on the Burt Range Shelf. On the latter, it outcrops at

Matheson Ridge and between Martin Bluff and Abney Hill. Its absence in the Kununurra area is probably due to erosion prior to Abney Sandstone deposition. The type section is 71 m thick and the thickest section (105 m) is at Dillon Spring.

Fossils: Trace fossils are common, with *Cruziana* preserved on the soles of the sandstone beds, and minor unidentified forms occur in sandstone and shale. Articulated and disarticulated bivalves, brachiopods, gastropods, and crinoids are locally abundant in all lithologies. In the type section, the lowest 40 m is most fossiliferous.

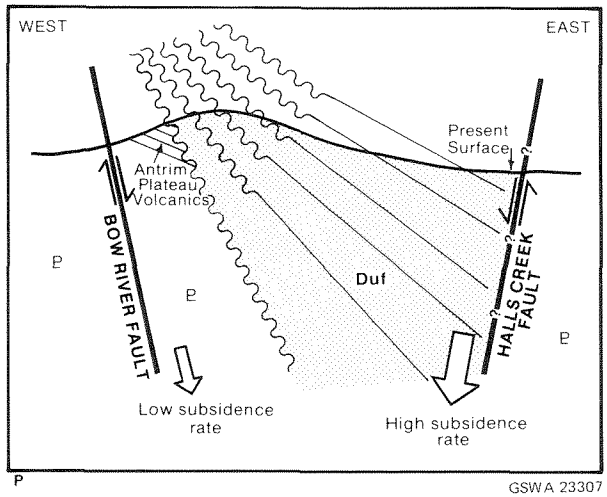

Figure 48. Diagrammatic cross-section through the Galloping Creek Formation (*Duf*) type section. The shallowing of dips up-section is interpreted to have been caused by relatively high subsidence in the east. Resulting wedge-shaped bodies may be accompanied by proximal intraformational unconformities on the thin edge. Proterozoic rocks shown as P.

GALLOPING CREEK FORMATION

Definition: The Galloping Creek Formation (Beere and Mory, 1986) consists of red-brown conglomerate, pebbly sandstone, sandstone and minor siltstone. The name is derived from Galloping Creek, and the type section is 10.5 km south of Glenhill homestead running eastwards from 16°21′40″S, 128°38′20″E to 16°24′10″S, 128°35′30″E. This unit was mapped by Veevers and Roberts (1968) as part of the Ragged Range Conglomerate, however, it differs in being significantly more feldspathic.

Lithology: The unit consists of thick sequences dominated by conglomerate, pebbly sandstone, and sandstone. The conglomeratic sequence consists of very thick conglomerate with minor sandstone beds and lenses, and it occurs in the lower part of the type section. The pebbly sandstone sequence, 5 km southeast of Glenhill, consists of thickly interbedded pebbly sandstone, feldspathic sandstone, arkose, and minor conglomerate. The sandstone-dominated sequence contains minor pebbly sandstone, conglomerate and siltstone and occurs 15 km east-southeast of Glenhill.

In the conglomerate sequence, the conglomerate is clast supported or, rarely, matrix supported. Clasts consist of rounded to well-rounded pebbles and boulders (up to 0.7 m), mainly of quartzite but with minor granitoid and volcanic clasts. In the pebbly sandstone and sandstone sequences, the conglomerate is commonly matrix supported and normally graded. Clasts reach 20 cm in diameter and consist mainly of quartzite, but volcanic and granitoid clasts are common. Laminated dolomite, massive dolomite, and limestone clasts are rare. In all sequences, massive bedding is common, with minor planar cross-bedding, and lesser parallel and trough cross-bedding. Pebbly sandstone and sandstone are feldspathic to arkosic, fine to coarse grained, poorly to well sorted, and biotitic. Pebbly sandstone grades into conglomerate and sandstone grades into siltstone. Bedding structures commonly include trough, planar, and low-angle cross-bedding, parallel bedding, and lamination. Siltstones are biotitic, and laminated or rippled.

Stratigraphic relationships: In the type section, the Galloping Creek Formation overlies the Antrim Plateau Volcanics with angular unconformity. Within the formation, dips decrease upsection, and this possibly indicate intraformational angular unconformities (Fig. 48). In central Ragged Range the unit overlies undifferentiated Cockatoo Group (probably Kellys Knob Sandstone) with angular unconformity (Fig. 49). The top of the Galloping Creek Formation is not seen.

Distribution and thickness: The unit occurs mainly in the southern Ragged Range Outlier around Smoke, Flying Fox, and Billy Goat Creeks. Small areas of outcrop occur in central Ragged Range 7.5 km northeast of Conglomerate Hill. Massive conglomerate 3.5 km west of Mount Brooking is tentatively assigned to the Galloping Creek Formation rather than the Ragged Range Conglomerate, as it has a similar palaeocurrent orientation. The type section is estimated to be 1600 m thick and the thickest section in central Ragged Range is about 2000m thick.

Fossils: Very poorly preserved, possible trace fossils and wood occur in the the pebbly sandstone sequence in the upper parts of the type section, and 5 km southeast of Glenhill. Body fossils are unknown.

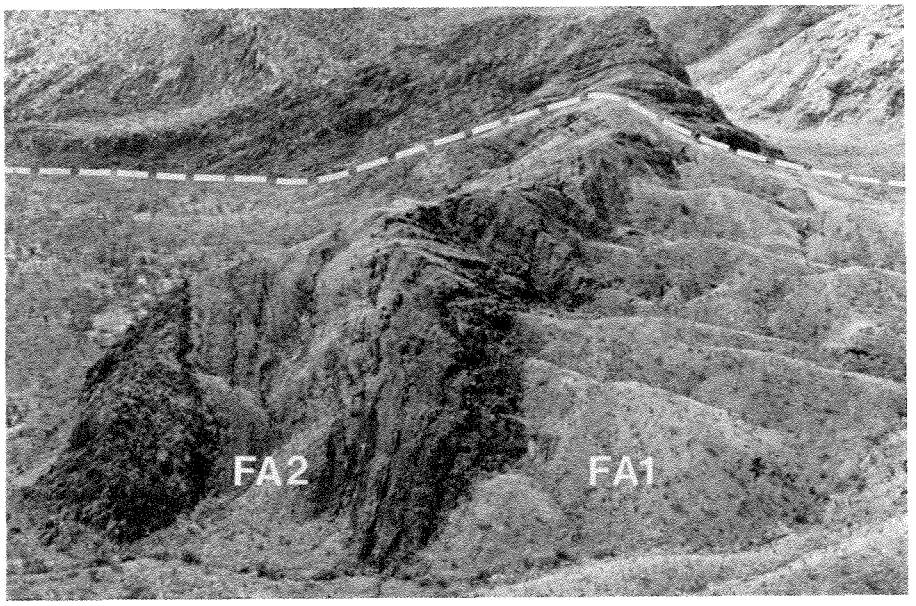

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Figure 49. Oblique aerial view of the Galloping Creek Formation in central Ragged Range. The fault block in the foreground comprises massive outcrop on the left which is probably Kellys Knob Sandstone and overlying steeply dipping (about 50°) Galloping Creek Formation. The Galloping Creek Formation consists of bedded pebbly sandstone (FA 2) and rounded, spinifex-covered hills of conglomerate (FA 1). Fault is shown by dashed line.

ABNEY SANDSTONE

Definition: The Abney Sandstone (Veevers and Roberts, 1968, amended by Beere and Mory, 1986) consists of red feldspathic and quartz sandstones, and rare siltstone. The type section is 1 km south of Abney Hill (base 15°44′00″S, 128°44′50″E; top 15°43′40″S, 128°45′30″E).

Lithology: In the type section, the sandstone is very fine to fine grained, well sorted and contains scattered coarse sand and granules. Thin to very thin parallel bedding is dominant, with minor lamination, interference, and longitudinal ripples. At Mount Cecil and Dillon Spring the unit is slightly coarser, consisting of very fine to medium-grained, moderate- to well-sorted sandstone, with scattered granules and pebbles up to 4 cm in diameter. Siltstone interbeds are rare. At Mount Cecil, medium planar and trough cross-bedding is also common. At Dillon Spring the sequence is parallel bedded, laminated, rippled, and trough and planar cross-bedded. Lower parts of the unit are fossiliferous and bioturbated, and cross-bedding becomes common in the upper parts.

Stratigraphic relationships: The Abney Sandstone lies conformably and gradationally between the Kununurra Formation and the Cecil Sandstone. The gradational contacts are shown in the type sections of the latter units. South of Abney Hill, the Kununurra Formation is missing and the Abney Sandstone disconformably overlies the Kellys Knob Sandstone.

Distribution and thickness: The Abney Sandstone occurs in the western Burt Range Shelf and Dillon Spring areas. The unit crops out mainly between Martins Bluff and Kununurra, and at Dillon Spring. The thickness varies considerably in the Kununurra–Abney Hill area, being 100 m thick in the type section, 150 m thick in a fault block 2.5 km south-southeast, and 45 m thick a further 5 km to the south-southeast. At Dillon Spring the unit is estimated to be 200 m thick.

Fossils: Brachiopods occur at the base of the unit near Abney Hill. Bivalves and trace fossils occur in parallel-bedded sandstone at Mount Cecil and in the lower part of the Dillon Spring sequence.

CECIL SANDSTONE

Definition: The Cecil Sandstone (Veevers and Roberts 1968, amended by Beere and Mory, 1986) consists of white, yellow, and light-brown quartz sandstone and pebbly sandstone, with minor conglomerate and siltstone. The type section, 4 km east-southeast of Kununurra (base 15°47′40″S, 128°46′50″E; top 15°45′40″S, 128°46′30″E) is probably faulted and repeated. A reference section to show the upper contact is here designated 2.5 km north-northwest from the base of the type section at 15°46′30″S, 128°46′20″E.

Lithology: The type section consists mainly of quartz sandstone with minor micaceous siltstone.

The sandstone is fine to medium grained, moderate to well sorted, locally pebbly, and parallel and trough cross-bedded. Thin interbeds of siltstone are usually laminated. At Matheson Ridge the unit is generally coarser, containing more pebbly sandstone and conglomerate. The sandstones also contain minor planar cross-bedding, lamination, and rare ripples. The conglomerate is sand supported and occurs in thin to medium lenses and trough infills. Siltstone and shale intraclasts are common. Laminated siltstone occurs in thick beds. The unit generally coarsens upwards, with cross-bedding and conglomerate becoming more common at the top.

Compared to the underlying Cyril Sandstone, the unit contains less conglomerate but more siltstone interbeds and siltstone-shale intraclasts. At Mount Cecil the unit is strongly silicified.

Stratigraphic relationships: In the type and reference sections the Cecil Sandstone lies conformably between the Abney Sandstone (below) and the Hargreaves Formation (above). At Matheson Ridge it conformably overlies the Ragged Range Conglomerate. The Maudoobar Sandstone is probably a very thick lens within the unit in the Matheson Ridge–Cockatoo Fault area.

Distribution and thickness: The Cecil Sandstone occurs only in the Burt Range Shelf and outcrops at Buttons Crossing, east of Kununurra, Mount Cecil, Matheson Ridge, and in the Northern Territory. Veevers and Roberts (1968) measured the type-section thickness as 224 m. However, the section has probably been repeated by faulting, as an unfaulted section immediately to the west, is about 110 m thick. The unit thickens to the east and is 300 m thick in the Northern Territory.

Fossils: Leptophloem occurs at Mount Cecil (Matheson and Teichert, 1948). Large wood fragments, probably *Leptophloem*, are locally common along the Cockatoo Fault. A fish plate stated by Veevers and Roberts (1968) to occur in the unit, in the eastern Hargreaves Hills, probably came from the Siggins Spring Member.

MAUDOOBAR SANDSTONE

Definition: The Maudoobar Sandstone (Beere and Mory, 1986) is a unit of uniform quartz sandstone. The name is derived from Maudoobar, the aboriginal name for Cockatoo Spring, 30 km southeast of Kununurra. The type section is 7 km north of the spring (base 15°53′10″S, 128°57′40″E; top 15°52′20″S, 128°58′30″E).

Lithology: The quartz sandstone is fine to medium grained and well sorted. Pebbles occur in the upper part of the type section. Barite rosettes and plates (up to 2 cm in diameter) form pseudomorphs after gypsum near the Cockatoo Fault. Thick planar cross-bedding is dominant, with minor medium to thick parallel bedding and rare trough cross-bedding.

Stratigraphic relationships: The Maudoobar Sandstone probably lies conformably within the Cecil Sandstone. In the type section the unit is gradationally overlain by the Cecil Sandstone, but the lower contact is not exposed. Further west, it is underlain by, and probably laterally equivalent to, the Cecil Sandstone.

Distribution and thickness: The unit is a wedge or lens extending from the type section west to Matheson Ridge and east into the Northern Territory. Lithologically similar sandstone in the Mount Rob–Gap Point Outlier with an identical palaeocurrent pattern may also be Maudoobar Sandstone. The type section is about 320 m thick and the maximum thickness may be 400 m.

HARGREAVES FORMATION

Definition: The Hargreaves Formation (Veevers and Roberts 1968, amended by Beere and Mory, 1986) consists of varicoloured sandstone with minor dolomite, limestone, and siltstone. The type section is in the eastern Hargreaves Hills (base 15°20′00″S, 128°34′20″E; top 15°19′50″S, 128°34′40″E). Lenticular bodies of distinctive lithology in the Hargreaves Formation have been given member status: the Siggins Spring Member and the Westwood Member.

The Siggins Spring Member (Beere and Mory, 1986) consists of white and yellow quartz sandstone and rare lenticular siltstone. The name is derived from Siggins Spring 7 km southwest of Ningbing homestead. The type section is 7.5 km southwest of the spring on the eastern side of the Hargreaves Hills (base 15°19′50″S, 128°34′40″E; top 15°19′40″S, 128°35′00″E) and was previously mapped as Cecil Sandstone (Veevers and Roberts, 1968).

The Westwood Member was originally defined as "the thick sequence of interbedded limestone or dolomite and fine to medium thin-bedded quartz sandstone in the Westwood Creek area" (Veevers and Roberts, 1968). The unit is here restricted to massive limestone and minor interbedded sandstone, near the base of the type section at Westwood Creek (14°52′S 128°30′E). The overlying sandstone, limestone, and dolomite are placed in the Hargreaves Formation.

Lithology: The sandstone is a very fine- to fine-grained, well- to very well-sorted, slightly glauconitic, quartz arenite. Medium-grained sandstone and pebbles are uncommon. Thin to medium parallel bedding is dominant, with lesser medium trough cross-bedding and minor massive bedding. Lamination, low-angle and planar cross-bedding, and longitudinal and asymmetric ripples are rare.

Dolomite occurs in thick to very thick units in the lower part of the sequence and may be sandy and shaly. Lamination, parallel, and massive bedding are common.

Parallel-bedded and massive dolomite contains body fossils and is bioturbated. Siltstone is massive or rippled and may be bioturbated. Limestone locally occurs around Westwood Creek and is parallel bedded and lacks abundant stromatoporoids.

In the Siggins Spring Member the quartz sandstone is very fine to medium grained, and moderate to well sorted. It contains quartzite pebbles and minor shale intraclasts. Medium to thin planar and trough cross-bedding is common, with minor, medium, parallel bedding.

The Westwood Member consists of massive boundstone and crudely bedded fossiliferous limestone. The boundstone consists mainly of stromatoporoids, *Renalcis*, and stromatolites. In the bedded limestone, bivalves and oncolites are locally abundant.

Stratigraphic relationships: On the Carlton Shelf the Hargreaves Formation lies conformably between the Kellys Knob Sandstone (below) and the Ningbing Group (above). The lower contact is poorly known, and is exposed only at Alice and Elephant Hills. The upper contact with Djillirri Limestone is exposed in the southwest and northwest Ningbing Range. Both Siggins Spring and Westwood Members are of limited lateral extent and are probably lenticular. The Westwood Member probably occurs in the upper part of the Hargreaves Formation.

In the Burt Range Shelf the Hargreaves Formation conformably overlies Cecil Sandstone east of Kununurra. In the subsurface it is overlain by the Buttons Formation, probably disconformably.

Distribution and thickness: The Hargreaves Formation occurs in the Burt Range and Carlton Shelves, outcropping mainly in the Hargreaves and Pretlove Hills. Strike faulting in these areas hinders measurement of a thickness.

Veevers and Roberts (1968), utilizing a series of marker beds in the Hargreaves Hills, estimated a thickness of about 600 m to the base of the Siggins Spring Member. Hargreaves Formation also occurs above this lenticular unit, and the total thickness may be up to 1300 m. An estimated 230 m occurs north of Matheson Ridge.

The Siggins Spring Member crops out in the eastern Hargreaves Hills and in a strike ridge 6.5 km to the north. Strike faulting is common in the area and the sequence may be repeated; if it is not, then the unit may be up to 700 m thick. The type section is incomplete and estimated to be 190 m thick.

The Westwood Member outcrops only in the type section, and 1 km along strike; it is 35 m thick.

Fossils and age: Fossils are sparse in the sandstone and dolomite. Bivalves, brachiopods, and trace fossils occur in the sandstone. In addition to these, oncolites, crinoids, and rare domical stromatolites occur in dolomite. The lamination in dolomite is probably of cryptalgal origin.

The fish plate found by Veevers and Roberts (1968) in the Siggins Spring Member type section is the only fossil known from this unit.

Fossils are very common in the Westwood Member. Besides stromatoporoids, stromatolites, and *Renalcis*, bony-fish plates and conodonts are also present in the massive limestone. Of those, only the conodonts have been described (Druce, 1969). In the bedded limestone a greater diversity of fossil groups are present, including corals, bivalves, algae, conodonts, ostracods, brachiopods, crinoids, gastropods, and stromatoporoids.

Brachiopods indicate an early Frasnian age (Roberts and others, 1967) and other fossil groups indicate a general Frasnian age (Veevers and Roberts, 1968).

MAHONY GROUP

The Mahony Group (Mory and Beere, 1985) occurs in the Ord Basin and consists of three formations, Glass Hill Sandstone; Boll Conglomerate; and Purralili Sandstone (Fig. 50). The group was initially examined by Hardman (1885) and later by Wade (1924), who believed the sandstones represented old sand dunes. Subsequently, it was mapped as Elder Sandstone and believed to be of Cambrian age (Matheson and Teichert, 1948, Traves, 1955), or Devonian age (Dow and others,

1964; Dow, 1980). In a revision of the stratigraphy, Mory and Beere (1985) split the 'Elder Sandstone' into the Cambrian Elder Subgroup and the disconformably overlying Devonian Mahony Group. Progressive overlap of the Cambrian sediments by the Mahony Group, between Glass Hill and Dixon Range, suggests major erosion in the southwest. The group outcrops only in the Hardman Syncline, mainly in the Bungle Bungle and Dixon Ranges, and north of White Mountain. The Boll Conglomerate and Purralili Sandstone area are really restricted units in the northwestern corner and eastern side of Bungle Bungle Range, respectively. Between 750 and 1 000 m of sediment occurs in the axis of the Hardman Syncline in the Bungle Bungle Range. Where the Boll Conglomerate and Purralili Sandstone are absent, the group is made up entirely of Glass Hill Sandstone. Based on thickness and height above base of the group, the Purralili Sandstone and Boll Conglomerate are not equivalent (Fig. 50).

Lithostratigraphy and genesis suggest that the Mahony and Cockatoo Groups are equivalent. Both are dominated by quartz sandstone and have minor conglomerate. Similar lithologies and stratigraphic positions, within the groups, suggest the following correlations (Fig. 46): the Glass Hill Sandstone with the Cyril and Cecil Sandstones; the Purralili Sandstone with the Kellys knob Sandstone; and the Boll Conglomerate with the upper parts of the Ragged Range Conglomerate and the Galloping Creek Formation. The correlation by Dow and others (1964) and Dow (1980) of the basal conglomerate of the Glass Hill Sandstone with the Ragged Range Conglomerate is rejected here, as the latter is much thicker and texturally coarser.

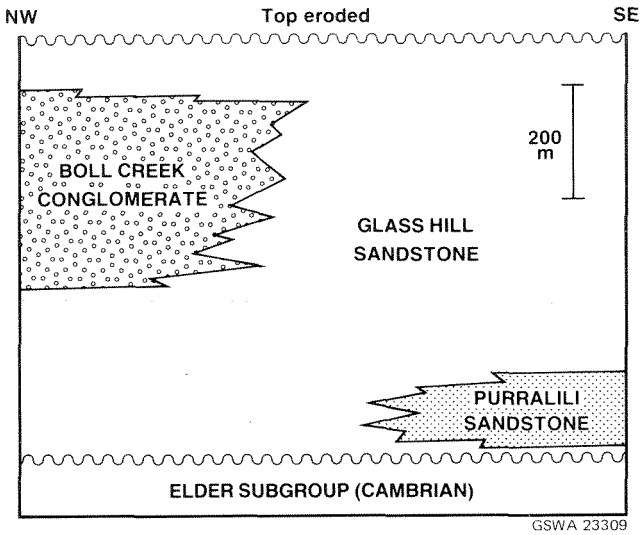

Figure 50. Diagrammatic stratigraphic relationships and thickness of the Mahony Group. Line of section is northwest to southeast across Bungle Bungle Range.

There is no internal evidence for the age of the Mahony Group. Rare bivalves north of White Mountain are too poorly preserved to identify. However, correlation with the Cockatoo Group suggests a Frasnian age. Using the correlations above, the base of the Boll Conglomerate (and its lateral equivalent in the Glass Hill Sandstone) divides the Mahony Group into sequences equivalent to the lower and upper Frasnian units of the Cockatoo Group.

GLASS HILL SANDSTONE

Definition: The Glass Hill Sandstone (Mory and Beere, 1985) consists of white and yellow, pebbly, quartz sandstone, with minor siltstone and conglomerate. The type section, at the south end of Dixon Range, begins at a small breakaway (17°41′40″S, 128°16′50″S) and continues northeast for 1 km (17°41′20″S, 128°17′00″E).

Lithology: The Glass Hill Sandstone is dominated by a unit of pebbly sandstone with minor siltstone and rare conglomerate. Pebbly sandstone is friable, medium to fine grained, and well sorted. Quartzite pebbles and locally abundant shale intraclasts generally comprise less than 1% of the rock, and rarely make up 5%. Pebbles are 1–3 cm in diameter and cobbles, up to 15 cm across, are rare. Medium trough and planar cross-bedding are dominant with minor, thick, parallel bedding and low-angle cross-bedding. Siltstone occurs as thin lenses and is massive, rippled, and contains mudcracks. Conglomerate is parallel and trough cross-bedded in thin to medium lenses.

A basal lens or wedge, 25 m thick, of conglomerate and sandstone outcrops between Bungle Bungle outcamp and Dixon Range, but is absent in the eastern Bungle Bungle Range. Conglomerate is clast- and matrix-supported, and contains mainly quartzite pebbles and cobbles. Clasts are up to 30 cm in diameter around Bungle Bungle outcamp, and decrease in size to the south and east. Trough and planar cross-bedding and parallel bedding are common. Sandstone is fine to coarse grained, moderate to well sorted, trough and planar cross-bedded, and laminated.

Stratigraphic relationships: The Glass Hill Sandstone disconformably overlies the Elder Subgroup, and forms the base of the Mahony Group everywhere. In the type section it overlies the Eagle Hawk Sandstone and to the northeast it overlies generally thicker sections of the Overland Sandstone. It encloses both the Purralili Sandstone and the Boll Conglomerate. The stratigraphically highest part overlies the Boll Conglomerate in the northwestern Bungle Bungle Range, and overlying strata are unknown.

Distribution and thickness: The Glass Hill Sandstone occurs throughout the Hardman Syncline. It forms most of the outcrops at Dixon Range, Bungle Bungle Range, and north of White Mountain. It also occurs in small outliers at Hardman Range and near Oakes Mountain. The type section is 200 m thick. The unit is about 10–20 m thick beneath the Purralili Sandstone, 8 km northwest of Doughboy Hill, and about 300 m thick beneath the Boll Conglomerate. Where both other units lens out, the Glass Hill Sandstone may be up to 1000 m thick.

Fossils: North of White Mountain, several species of poorly preserved bivalves occur in pockets in the basal sandstone.

PURRALILI SANDSTONE

Definition: The Purralili Sandstone (Beere and Mory, 1986) consists of white, uniform, quartz sandstone. The name is the aboriginal word for Mount Buchanan and it replaces "Buchanan Sandstone" as defined by Mory and Beere (1985) since that name has been previously cited, without a definition, in Dow and Gemuts (1969). The type section is located 5.5 km south of Mount Buchanan (base 17°22′20″S, 128°36′50″E; top 17°21′50″S, 128°36′00″E). The upper part of the unit, which is inaccessible in the type section due to cliff exposures, is seen in a reference section 3 km to the southwest (base 17°23′30″S, 128°35′00″E; top 17°23′00″S, 128°33′50″E).

Lithology: The sandstone is medium grained and well sorted; well-rounded frosted grains are common. Coarse and fine-grained sandstone is uncommon. Lower parts of the unit contain medium to thick planar cross-bedding, minor parallel bedding and low-angle cross-bedding. Low-angle cross-bedding is dominant in upper parts of the unit; planar cross-bedding, parallel and massive bedding are minor.

Stratigraphic relationships: The Purralili Sandstone is probably a lens within the Glass Hill Sandstone. In the reference section the upper contact is sharp and conformable, but 6 km to the south the units interfinger. The lower contact is not exposed.

Distribution and thickness: The unit outcrops along the eastern side of Bungle Bungle Range, and in isolated low outcrops to the east. About 130 m is exposed in the type area and the total thickness is unlikely to exceed 140 m.

BOLL CONGLOMERATE

Definition: The Boll Conglomerate (Beere and Mory, 1985) consists of red and white conglomerate, pebbly sandstone, sandstone, and rare siltstone. The type section is the west wall of a northerly oriented gorge, (Fig. 51) 3 km east-

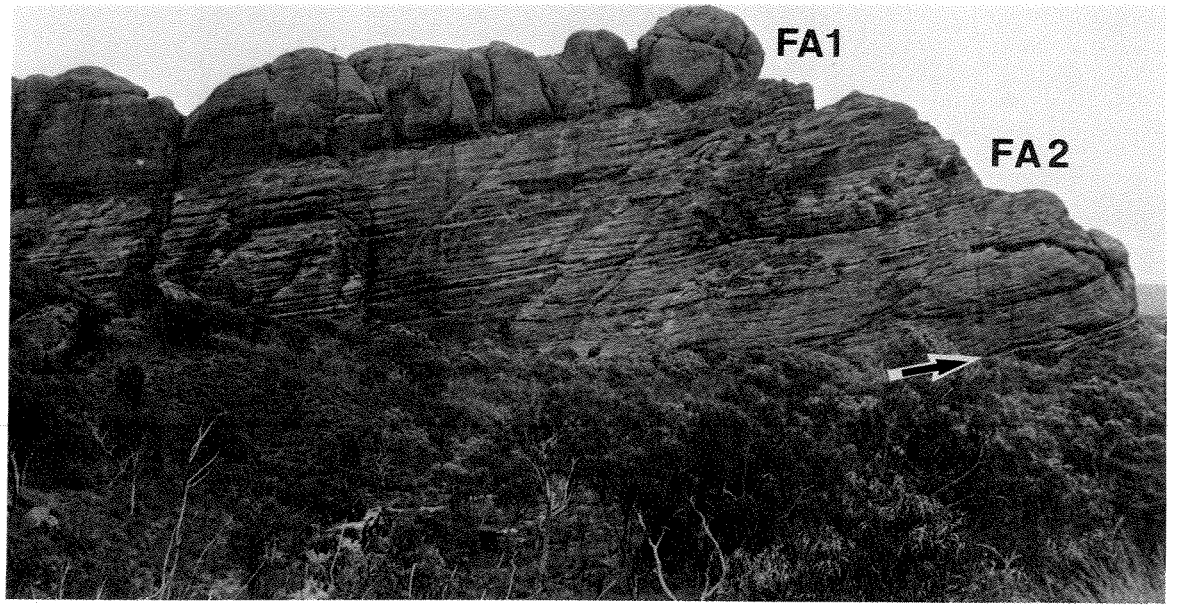

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Figure 51. Type section of the Boll Conglomerate, north Bungle Bungle Range. Cliff-forming massive conglomerate (FA 1) overlies bedded conglomerate, pebbly sandstone, and sandstone (FA 2). FA 2 is conglomeratic at the base, and most beds are laterally impersistent. The lower conformable contact with Glass Hill Sandstone is on the far right (arrowed). Hill is about 200 m high.

southeast of Bungle Bungle outcamp (base 17°21′10″S, 128°22′10″E; top 17°22′40″S, 128°22′40″E).

Lithology: Two lithological units are present (Fig. 51): an upper conglomerate, 200 m thick, with rare sandstone; and a lower unit, 150 m thick, of thick to very thickly interbedded conglomerate, pebbly sandstone, sandstone, and rare siltstone. Conglomerate in the upper unit is clast supported. Clasts are rounded to well rounded; quartzite cobbles and pebbles reach 0.9 m diameter. Medium to very thick massive bedding is dominant with rare trough cross-bedding. In the lower unit, the conglomerate is clast- and sand-supported. It is also finer grained, consisting of quartzite pebbles and cobbles, up to 18 cm diameter, and rare siltstone boulders up to 1 m. Trough cross-bedding is more common. Pebbly sandstone grades into conglomerate and sandstone. Thin to medium trough cross-bedding is dominant, with rare parallel bedding and imbrication. Sandstone is medium to very fine grained, well sorted, and medium to thick trough cross-bedded with minor lamination. Thin to thick siltstone lenses and beds are massive.

Stratigraphic relationships: The Boll Conglomerate is a lens or wedge within the Glass Hill Sandstone. In the type section the lower contact is sharp but conformable. The upper part of the unit is inaccessible due to the cliff-forming massive conglomerate, and air-photo interpretation indicates it is overlain by the Glass Hill Sandstone.

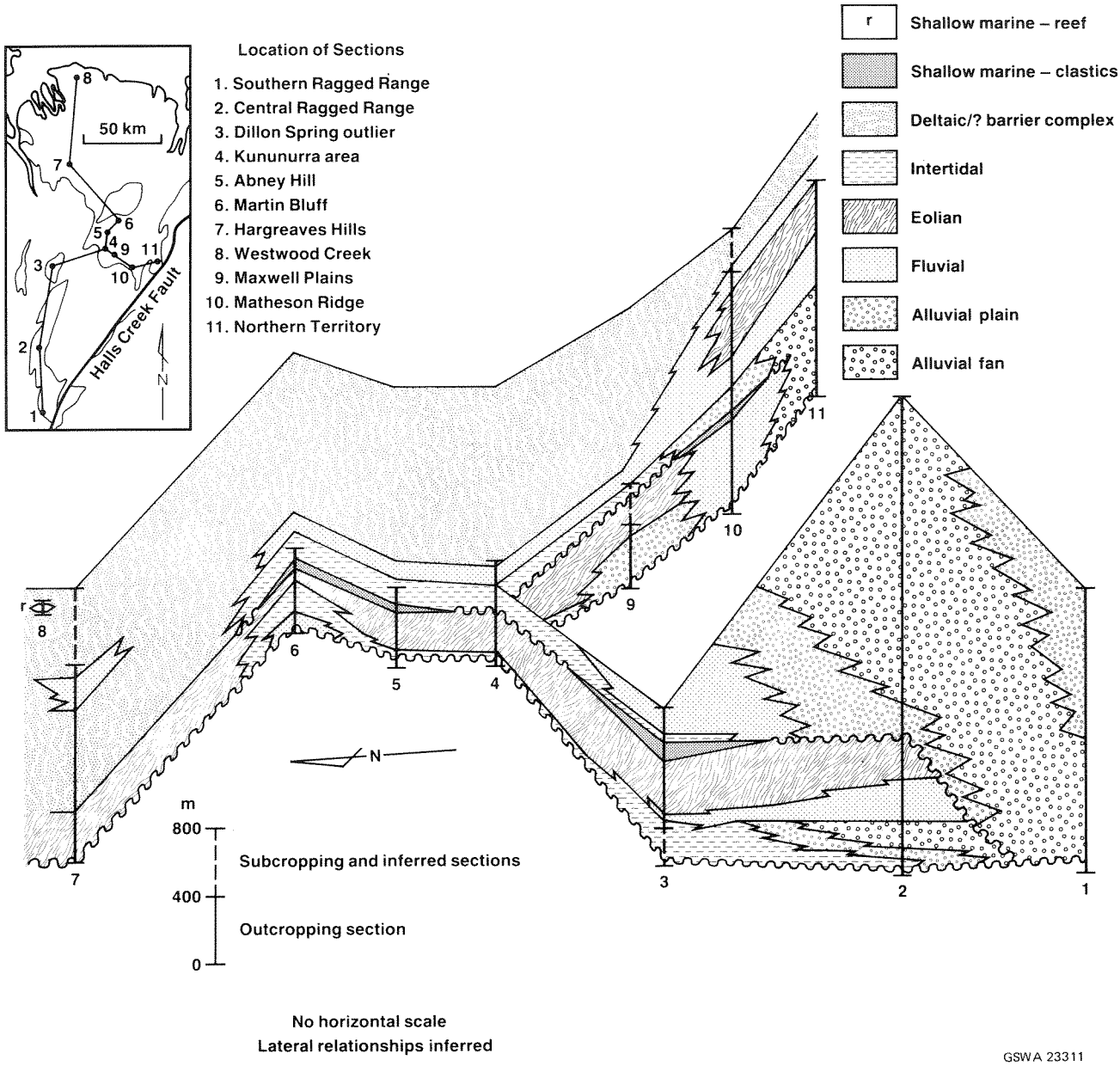

Figure 52. Distribution and diagrammatic relationships of depositional environments in the Cockatoo Group.

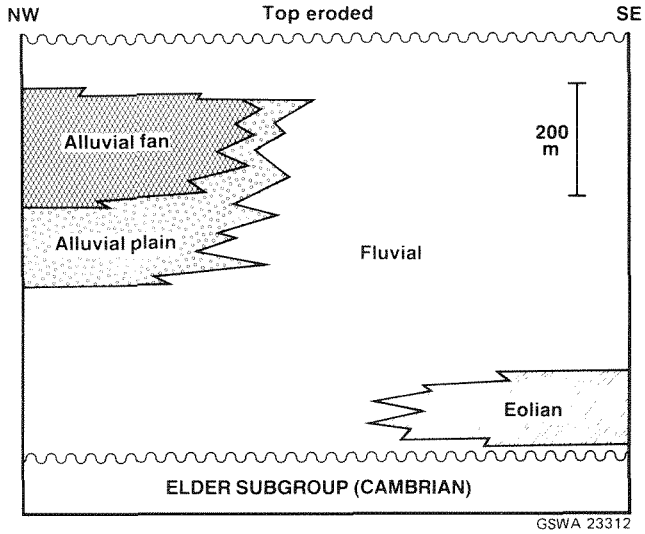

Figure 53. Distribution and diagrammatic relationships of depositional environments in the Mahony Group.

Distribution and thickness: The Boll Conglomerate outcrops in a narrow belt on the northern side of Bungle Bungle Range. A thin tongue extends 8 km south along the top of the range to the head of Piccaninny Creek. The type section is 350 m thick.

FACIES ANALYSIS OF COCKATOO AND MAHONY GROUPS

The Cockatoo and Mahony Groups were deposited in continental and shallow-marine settings. The stratigraphic and geographic distributions of these are shown in Table 3 and Figures 52 and 53. Most formations were deposited primarily in one environment, although formation boundaries do not always coincide with environmental changes.

TABLE 3. STRATIGRAPHIC DISTRIBUTION OF ENVIRONMENTS, COCKATOO GROUP

	Unit	*Environment*						
		Reef	*Shallow marine*	*Deltaic*	*Tidal*	*Fluvial*	*Eolian*	*Alluvial fan*
COCKATOO GROUP	Hargreaves Formation	—	R	D	M	M	—	—
	Westwood Member	D	—	—	—	—	—	—
	Siggins Spring Member	—	—	—	—	D	—	—
	Cecil Sandstone	—	—	—	—	D	—	—
	Maudoobar Sandstone	—	—	—	—	—	D	—
	Galloping Creek Formation	—	—	—	—	M	—	—
	Abney Sandstone	—	—	—	D	M	—	—
	Kununurra Formation	—	D	—	—	—	—	—
	Kellys Knob Sandstone	—	—	—	M	M	D	—
	Cyril Sandstone	—	—	—	—	D	—	—
	Steeple Peak Sandstone	—	—	—	D	M	—	—
	Ragged Range Conglomerate	—	—	—	R	—	—	D
MAHONY GROUP	Boll Creek Conglomerate	—	—	—	—	—	—	D
	Purralili Sandstone	—	—	—	—	—	D	—
	Glass Hill Sandstone	—	—	—	R	D	—	—

D = dominant M = minor R = rare

TABLE 4. ALLUVIAL-FAN FACIES, COCKATOO AND MAHONY GROUPS

LITHOLOGY	*BOLL CONGLOMERATE*		*RAGGED RANGE CONGLOMERATE*		*GALLOPING CREEK FORMATION*	
FA1:						
Conglomerate	*Gm* *Gt* clasts 0.3–0.4 m diameter (average) 0.9 m diameter (max)	Medium to thick bedded (0.3–1.5 m) Minor; 0.3–1 m thick sets	*Gm* *Gt* *Ga*	Thick bedded 0.5–3.0 m, minor imbrication Rare; 0.3–1 m thick sets Rare; clasts 1.2 m (max)	*Gm* *Gp*	Medium to thick bedded 0.3–2 m, minor imbrication Minor; 0.5–1.5 m thick sets, clasts max 0.7 m
Sandstone	*Sh, Sl*	Rare; thin drapes	*Sh, Sl*	Minor; thin to medium lenses and thick beds	*Sh, Sl* *St, Sp*	Minor; medium to thick beds and lenses, scour fills, biotite-rich tops Rare; rare mudcracks
FA2:						
Conglomerate	*Gm*	Medium to thick beds and lenses, minor imbrication	*Gm*	Medium to very thick bedded, rare imbrication	*Gm*	Thin- to thick-bedded minor graded beds
	Gt	Medium to thick sets, minor channel fills, clasts 3–10 cm (average), 18 cm (max), scattered siltstone to 1 m	*Gt* *Ga*	Rare; medium to thick sets Rare; clasts 0.4 m (max)	*Gp* *Ga*	Minor; medium to thick sets Clasts 0.2 m (max)
Pebbly sandstone	*St* *Sa* minor fining-up sequences 2–3 m thick	Thin to medium sets; channel fills Rare; with imbrication	*St* *Sp*	Medium sets	*St* *Sa*	Thin to thick sets Minor; thin sets
Sandstone		Very fine to medium grained;		Very fine to fine grained;		Fine to coarse grained, poor to well sorted arkose, biotitic;
	St *Sh*	Medium to thick sets Minor; medium to thick beds mud intraclasts locally common, rare mudcracks	*Sh* *St, Sp* *Sr*	Thin to very thick beds; minor parting lineation, fining-up sequences 10–20 cm thick Minor; thin to thick sets Minor; interference and longitudinal types minor mudcracks	*Sh* *Sp*	Thin to thick beds Minor; poor load casts, possible trace fossils
Siltstone	*Fm*	Minor; 0.1–1 m thick beds		Absent		Absent

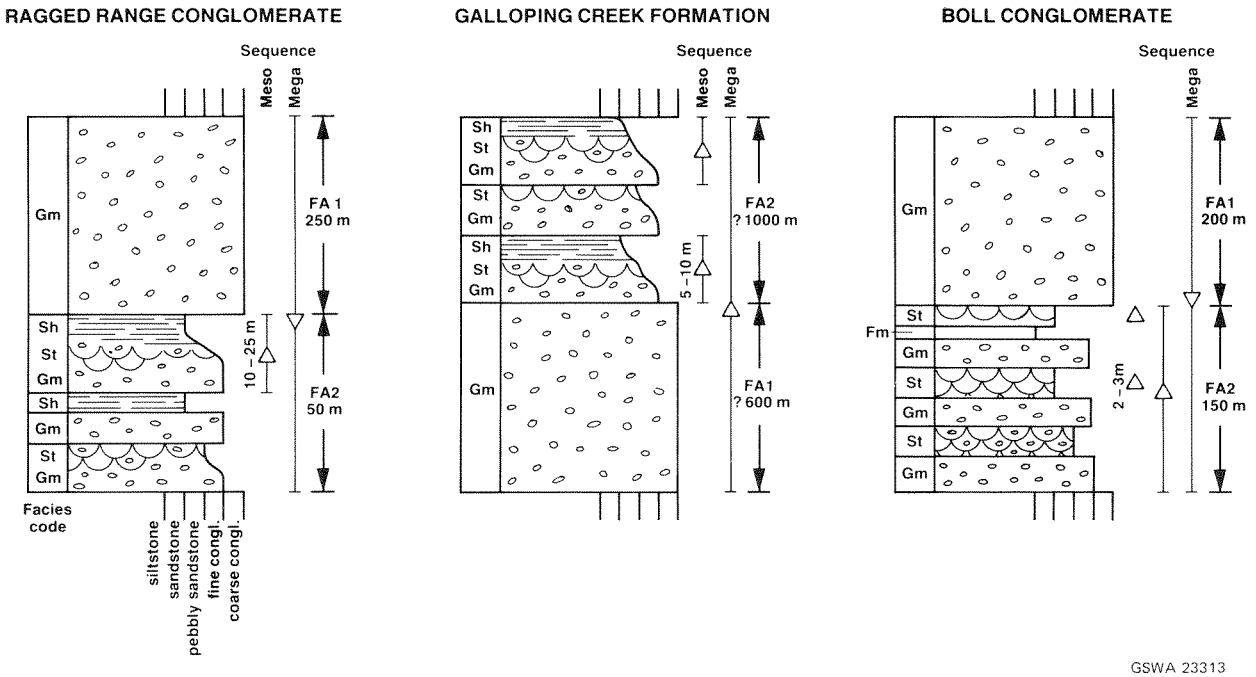

Figure 54. Diagrammatic relationships of alluvial-fan facies and facies associations. Key to symbols in Figure 3.

ALLUVIAL FAN

Alluvial-fan environments are interpreted for the Ragged Range Conglomerate, Galloping Creek Formation, and Boll Conglomerate. Two facies associations (FA 1 and FA 2) containing several facies are recognized in this environment. Detailed descriptions are given in Table 4 and a general description follows.

Facies associations

Facies association 1 (FA 1): This consists of 200–600 m of pebble to boulder conglomerate with minor sandstone (Fig. 54). Clast-supported (or rarely, matrix-supported) massive conglomerate (facies *Gm*, Fig. 55) is dominant. Imbrication is uncommon, due to spherical clast shape. Minor structures include medium to thick planar and

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Figure 55. Massive pebble to boulder conglomerate (facies *Gm*) interbedded with laminated sandstone (facies *Sl*). Clast imbrication in the lower bed shows a current direction from left to right. Ragged Range Conglomerate, central Ragged Range.

trough cross-bedding (*Gp* and *Gt*) and parallel bedding (*Ga*). Sandstone occurs mainly in medium to thick discontinuous beds and lens-filling scours in the underlying conglomerate, or as thin drapes. Lamination (*Sh*) and low-angle cross-bedding (*Sl*) are common with rare planar and trough cross-beds (*Sp* and *St*). Some sandstone beds fine-upwards into silty, micaceous and mudcracked tops.

The coarse grain size and bedding structures indicate very high-energy alluvial-fan deposition. The facies assemblage is similar to the Scott assemblage (Miall, 1982), where deposition occurs in shallow braided rivers on fans lacking debris flows. The massive bedding and clast-supported framework of facies *Gm* suggests it was deposited as either longitudinal bars or lag deposits. The minor matrix-supported conglomerates were possibly deposited by debris flows. Cross-bedded conglomerate (*Gt* and *Gp*) probably represents channel fills and sinuous and straight-crested bars. Sandstone horizons represent relatively lower energy deposition, either in bypass channels during floods or in active channels during the waning periods of floods. However, plane beds (*Sh*), scour fills or antidunes (*Sl*), and trough cross-bedding (*St*) indicate there was still high energy (Harms and others, 1982). Fining-upward sequences were probably deposited during the final waning stages of floods. Subaerial desiccation developed mudcracks.

Facies association 2 (FA 2): This consists of between 50 m and 1000 m of conglomerate, pebbly sandstone and sandstone (Fig. 54). The conglomerate, which is polymodal, is clast and matrix supported. Beds and lenses of conglomerate, up to 1 m thick, have eroded and non-eroded bases. Massive conglomerate, locally imbricated, is dominant. Minor facies include planar cross-bedding, trough cross-bedding (*Gp* and *Gt*; Fig. 56), and medium to thick parallel bedding (*Ga*).

Pebbly sandstone is dominantly thin to medium trough cross-bedded (*St*) with locally common planar cross-bedding (*Sp*), and minor parallel bedding (*Sa*). Fining-up sequences 2–3 m thick occur in the Boll Conglomerate.

Sandstones are dominantly laminated in the Ragged Range Conglomerate and Galloping Creek Formation, or trough cross-bedded in the Boll Conglomerate. Sequences dominated by laminated sandstone (*Sh*) include minor thin to thick cross-bedding (*St* and *Sp*). Interference and longitudinal ripples (*Sr*), parting lineation, mudcracks, load casts and possible trace fossils are locally present. In the Ragged Range Conglomerate, fining-up microsequences 10–20 cm thick begin with laminated sandstone (*Sh*) with parting lineation, and pass up into rippled sandstone (*Sr*). Trough cross-bedded sandstones (*St*), include minor medium to thickly laminated (*Sh*) beds, with locally common mudstone clasts, and rare mudcracks. Continuous beds of massive siltstone up to 1 m thick occur only in the Boll Conglomerate.

Facies in FA 2 may also occur in fining-up and non-cyclic sequences, 5–25 m thick (mesosequences), with the thickest mesosequences being in the Ragged Range Conglomerate. Cyclic sequences consist mainly of conglomerate (*Gm*) passing upward into pebbly sandstone (*St*) and

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Figure 56. Trough cross-bedded pebbly sandstone (facies *St*) and conglomerate (*Gt*) with several thin sand horizons. Boll Conglomerate type section (FA 2).

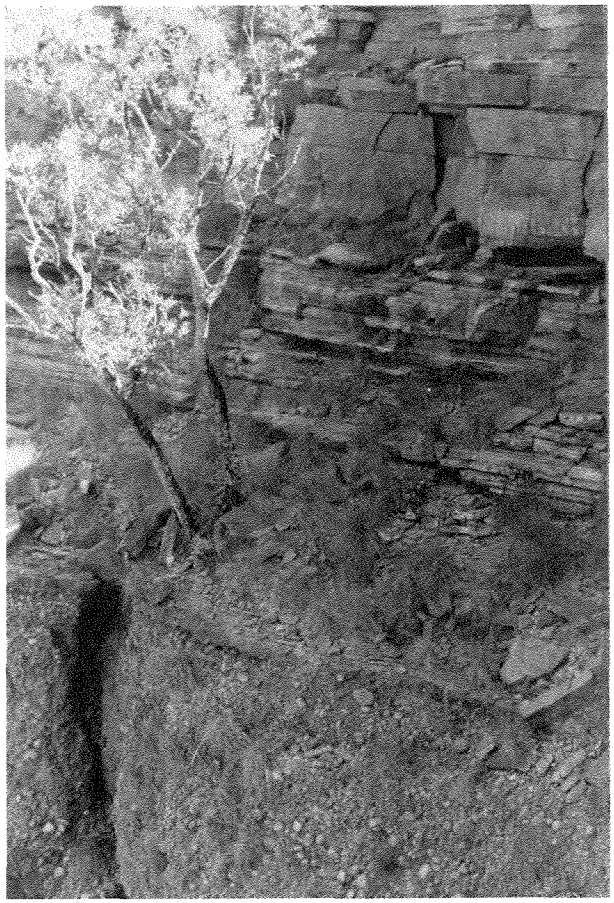

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Figure 57. Thick laminated sandstone (facies *Sh*) sharply overlying massive conglomerate (facies *Gm*) forming a non-cyclic mesosequence in FA 2. Ragged Range Conglomerate, 3 km south of Conglomerate Hill.

then sandstone (*Sh*). Non-cyclic mesosequences consist of thick horizons of one lithology or facies (Fig. 57), and are common in the Boll and Ragged Range Conglomerates (Fig. 54). In the type section of the Boll Conglomerate, FA 2 has an overall fining-upward trend, as conglomerate facies are more common at the base (Figs 51 and 54).

This association is finer grained than FA 1, indicating lower energy distal-alluvial deposition. It is similar to the Donjek assemblage (Miall, 1982) where sedimentation occurs in braided rivers with well-defined active channels, and partially to entirely inactive interchannel areas. Palaeocurrent directions in these streams are similar to those on the alluvial fans (Ragged Range Conglomerate, Galloping Creek Formation, Fig. 58), indicating that deposition occurred on an alluvial plain (Rust, 1979). The diversity of lithologies and facies in this association reflects highly varied depositional processes and bed forms. Deposition occurred mainly as a combination of longitudinal bars (*Gm* and *Ga*), dunes (*St*) and plane beds (*Sh*). Minor depositional features include channel fills (*Gt*), transverse and linguoid bars, straight-crested dunes (*Gp* and *Sp*), scourfills or antidunes (*Sl*), and ripples (*Sr*). Thick sequences of plane beds (*Sh*) represent prolonged periods of either sheetflood deposition in shallow interchannel areas or high-energy deposition in channels.

Thick siltstone beds accumulated in inactive channels or overbank areas, suggesting prolonged non-deposition, or channel stabilization.

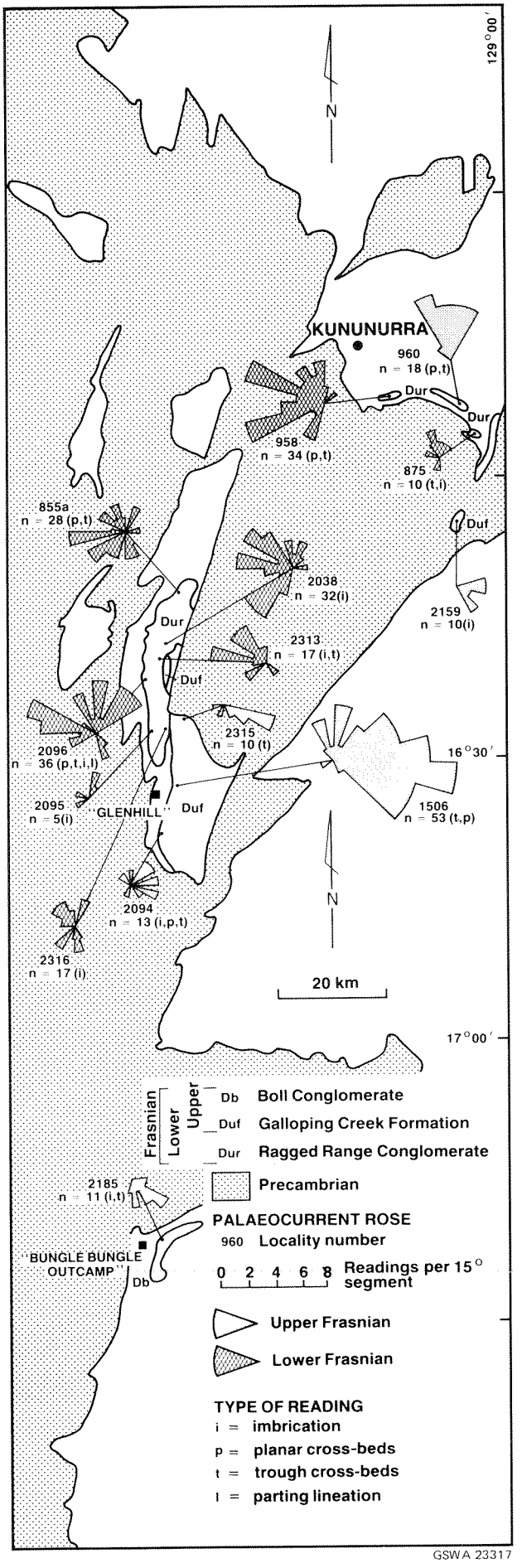
Fining-up sequences up to a few metres thick are due to either bar aggradation or the waning stages of single flood periods. Fining-up mesosequences 5–10 m thick in the Galloping Creek Formation were possibly formed by gradual abandonment or bar aggradation in deep channels. The thicker mesosequences (up to 25 m) were possibly deposited in channels of a larger scale than those predicted by the Donjek model (3–7 m deep). Non-cyclic mesosequences were possibly deposited in short-lived single-flood channels where fining-up cycles could not develop.

Palaeocurrents and provenance

Alluvial sediments occur in both lower and upper Frasnian lithostratigraphic units. The derivation of sediments and direction of transport are different in each.

Lower Frasnian sediments consist of the Ragged Range Conglomerate at Ragged Range, Maxwell Plains, and lower parts of the Northern Territory sequence. Transport in both FA 1 and the FA 2 (Fig. 58) is towards the west and north. Sediments have a mature, quartz-rich mineralogy. Most clasts are rounded to well-rounded quartz and quartzite, although tabular angular-shale clasts are common locally, due to reworking of basement rocks. The sandstone is a quartz arenite, with arkose occurring close to granitic basement (southern Ragged Range).

Textural maturity and general transport directions indicate a sedimentary provenance in the east. At Ragged Range the sediments were probably derived from the Carr Boyd Group, outcropping in the Carr Boyd Ranges (Plumb, 1968). In the Northern Territory–Matheson Ridge area, the sediments were probably derived from the Duerdin Group, outcropping on the Sturt Block (Pontifex and Sweet, 1972).



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Upper Frasnian sediments occur at the southern end of Ragged Range and Mount Hensman (Galloping Creek Formation), near Bungle Bungle outcamp (Boll Conglomerate), Matheson Ridge, and the Northern Territory (Ragged Range Conglomerate). In the Galloping Creek Formation, clasts consist mainly of quartz and quartzite; but granitic, volcanic, and calcareous clasts are also present. Conglomerate matrix and sandstones are arkosic, and a mixed sedimentary and granitic provenance is indicated. Transport directions are to the northeast and southeast in both FA 1 and FA 2 (Fig. 58). The sediments were probably derived from the Bow River Granite and Carr Boyd Group, outcropping to the west and south (Dow and Gemuts, 1969). The quartzite conglomerate in the Galloping Creek Formation is very thick and indicates a large, sedimentary source area. However, the Carr Boyd Group occupies a small area, and it is possible that the sediments were reworked from Ragged Range Conglomerate (lower Frasnian) and eroded it completely.

In the Ragged Range Conglomerate the quartzite clasts and arkosic matrix indicate a mixed sedimentary and granitic provenance. Transport was to the north in FA 2 (Fig. 58). The sediments were probably derived from the Bow River Granite which outcrops near the Carr Boyd and Cockatoo Faults, to the south and east.

The Boll Conglomerate has a mature mineralogy consisting of quartz and quartzite clasts in a matrix of quartz arenite. Transportation to the southeast in FA 2 (Fig. 58) indicates derivation from quartz sandstone and siltstone to the north in the Osmond Range (Dow and Gemuts, 1969).

Tectonics and fan development

Thick accumulations of alluvial sediments indicate repeated fault movements, rather than erosion of initial topography or fault scarps (Heward, 1978). Mesosequences and megasequences, tens to hundreds of metres thick, provide evidence for long-term fan behaviour in alluvial systems.

In the lower Frasnian, the Ragged Range Conglomerate at Ragged Range is a coarsening-up megasequence. It is 290 m thick and consists of

Figure 58. Alluvial-fan sediments; outcrop and palaeocurrent distribution.

FA 1 overlying FA 2, (Fig. 54), whereas in the Northern Territory it consists of FA 1 only. In both areas sediments were derived from the east. Coarsening-up megasequences reflect tectonic uplift of the hinterland (Heward, 1978). When the hinterland erosion rate exceeds relative uplift, prolonged fan entrenchment occurs and the active-fan segment shifts downstream, causing coarse proximal deposits to prograde over distal deposits at the fan toe. At Ragged Range deposition occurred at the toe of a fan. Movement along the Revolver Creek Fault, 10 km to the east, probably led to the shedding of sediments.

Intraformational angular unconformities at Ragged Range show syndepositional faulting in the basin. The fining-up mesosequences (10 – 25 m) in FA 2 may be the result of short-term fanhead entrenchment which localized sediment deposition in a single channel and temporarily left abandoned-fan surfaces elsewhere (Heward, 1978). Sudden initiation of sediment supply, followed by gradual abandonment, would develop a fining-up sequence. In the Northern Territory, the thick ungraded sequence was probably deposited close to the mountain front, where the lateral shifting of fan environments has little effect (Heward, 1978). Sediments were derived from the east and were probably shed from the Halls Creek Fault. Alluvial sediments pass westwards into fluvial braided streams, at Matheson Ridge, indicating that the complex of fan and plain was about 9 km wide.

Faulting was more widespread during the upper Frasnian. Sedimentation continued in the Northern Territory and was initiated in the areas of Bungle Bungle outcamp and southern Ragged Range.

The Boll Conglomerate is a coarsening-up megasequence (Fig. 54) derived from the Osmond Range to the north. Fan deposition was away from the mountain front, and the fan probably formed due to movement along the Osmond Fault. FA 2 is a fining-upward megasequence, indicating scarp retreat and erosion of the hinterland during a tectonically inactive phase. Non-cyclic mesosequences were possibly caused by short-term fanhead entrenchment. The transition from alluvial environments into braided streams in northwestern Bungle Bungle Range indicates the fan complex was about 20 km wide.

The Galloping Creek Formation consists of a coarsening-up megasequence in central Ragged Range and a fining-up megasequence in southern Ragged Range. Sediments were probably derived from the west. Large thicknesses of the conglomerate in both sections suggest numerous phases of faulting and proximity to faults. The fining-up and coarsening-up megasequences indicate decreasing fault intensity and continuous activity, respectively. The dominance of conglomerate, in the lower part of the southern section and in the upper part of the northern section, indicate that both tectonism and the basin depocentre shifted northwards. Identification of the active faults is difficult. The Bow River and Glenhill Faults were possibly active, as they are close to the present sediment distribution, and the hinterland rocks generally match the sediment provenance. However, the thickest section of sediment in central Ragged Range occurs on what should be the upland side of the Glenhill Fault. Additionally, the trend of the Bow River Fault is parallel, instead of perpendicular, to the easterly depositional dip of the alluvial sediments. Faults further to the west (such as the Dunham River Fault) lack significant granite in the hinterland to supply arkosic sediments, and were pobably not active. Shallowing of dips in the type section (Fig. 48) was possibly caused by high subsidence adjacent to the Halls Creek Fault.

In the Northern Territory, the Ragged Range Conglomerate is a non-graded sequence similar to that in the lower Frasnian, indicating continued movement along the Halls Creek Fault.

FLUVIAL

Fluvial environments dominate the Cecil, Cyril, and Glass Hill Sandstones, and the Siggins Spring Member; they also occur in the Galloping Creek Formation and Abney Sandstone. Isolated occurrences in other units (Table 3) will not be discussed here.

A large number of facies have been recognized and their description and distribution in the formations are given in Table 5. Four facies associations have been recognized, based on the relative abundance of these facies and the presence or absence of cycles.

The lack of extensive shale and siltstone beds suggests that these facies associations were deposited as braided streams, rather than in meandering and anastomosing river systems where these lithologies are common (Walker and Cant, 1979; Miall, 1982).

Facies associations

Facies association 3 (FA 3): This consists mainly of trough and planar cross-bedded quartz sandstone and pebbly sandstone (*St* and *Sp*). Parallel-bedded (*Sa*) and low-angle cross-bedded (*Sl*) sandstones are minor; laminated sandstone (*Sh*) is rare. There

TABLE 5. FLUVIAL FACIES, COCKATOO AND MAHONY GROUPS

FACIES	*CECIL SANDSTONE CYRIL SANDSTONE*	*GLASS HILL SANDSTONE*		*GALLOPING CREEK FORMATION*	*ABNEY SANDSTONE*	*HARGREAVES FORMATION*
			Basal Conglomerate			*Siggins Spring Member*
	Fine to medium quartz sandstone and pebbly sandstone; minor conglomerate and micaceous siltstone	*Fine to medium quartz sandstone, minor pebbly sandstone and siltstone; rare pebble conglomerate*	*Pebble-boulder conglomerate, pebbly sandstone, and sandstone*	*Fine to medium feldspathic quartz sandstone and arkose; minor conglomerate and micaceous siltstone*	*Very fine to medium feldspathic quartz sandstone, scattered granules and pebbles*	*Fine to medium quartz sandstone, scattered granules and pebbles; rare shale*
CONGLOMERATE:						
Gt trough cross-bedded	Thin to medium beds (Cecil)	Thin to medium lenses	Also *Gp*, thick sets	Medium to thick sets	—	—
Ga parallel bedded	Medium to very thick beds (Cyril)	Minor imbrication	Medium to thick sets			
	Sand supported, polymodal, quartzite pebbles to boulders <25 cm	Sand supported, 1–3 cm average, <15 cm max., quartzite, rare shale	Clast-and sand-supported, polymodal, 2–5 cm average, <30 cm max., quartzite	Sand supported, pebbles and small cobbles <12 cm max., quartzite, minor volcanics	—	—

SANDSTONE:							
St	trough cross-bedded	Thin to medium sets	Medium sets	Thin to medium sets	Minor; thin sets	Thin to medium sets	Thin to medium sets
Sp	planar cross-bedded	Medium sets	Medium sets	Thin to thick sets	Minor; thin to very thick beds	Rare; thin to medium sets	Thin to medium sets
Sa	parallel bedded	Thin to medium beds	Minor; medium to thick beds	—	—	Minor; medium to thin beds	Minor; medium sets
Sl	low-angle cross-bedded	Locally abundant (Cyril Sandstone)	Minor; medium to thick beds	—	Thin to medium beds	Minor	—
Sh	laminated	Rare (Cecil Sandstone)	Rare	Thin to thick beds, parting lineation	Minor; medium to thin beds	Rare; medium to thick beds, parting lineation	—
Sr	rippled	Rare	Rare	—	—	Rare	—
SILTSTONE:							
Fh	laminated	Thin to thick beds and lens	Thin lens	—	Thin to medium lenses	—	Rare
Fr	rippled		Minor; asymmetric				
	other structures	Minor mudcracks; rare trace fossils; local concentrations of *Leptophloem*	Minor mudcracks and contorted beds	—	—	—	—
RELATIVE ABUNDANCE		*St, Sa, Sp>Sl, Ga, Gt> Sh, Sr, Fh, Fr*	*St, Sp>Sa, Sl>Fr, Fm, Gt, Ga*	*Ga, Gt, Gp, St, Sp>Sh (cyclic)*	*Sl, Sp>Sh, St>Ga, Gt, Fm*	*St>Sa>Sp, Sh, Sr*	*Sp, St>Sa*

are variable amounts of parallel and trough cross-bedded conglomerate (*Ga* and *Gt*), also laminated, rippled and mudcracked siltstones (*Fh* and *Fr*, Fig. 28). Fining-up or coarsening-up sequences are absent. This association occurs in the Cyril Sandstone (490 m thick), Cecil Sandstone (700 m maximum), Siggins Spring Member (220 m), and the Glass Hill Sandstone (300–1000 m) above the basal conglomerate. The Glass Hill Sandstone at northeast Bungle Bungle Range consists of stacked units up to 10 m thick. Each unit, containing several facies, is characterized by varying proportions of clay matrix and siltstone intraclasts. The textural differences may also control the common development throughout the range of thick bands, on weathering surfaces subparallel to bedding. The bands are horizons of surface silicification which may be traced over several hundred metres along strike. The Siggins Spring Member consists entirely of planar and trough cross-bedded sandstone with minor parallel-bedded sandstone.

The lack of cycles in FA 3 indicates deposition in shallow rivers, because cycles develop due to relief within channels, or on bars (Cant, 1982). Thick horizons with the same texture possibly represent deposition over several flood periods in a relatively short-lived river system. Stacked sequences are the result of deposition from successive river systems punctuated by short breaks. More homogeneous sequences may result from channels being longer lived. Major bed forms consisted of sand waves and dunes (*Sp* and *St*). Minor bed forms included sandy and gravelly longitudinal bars (*Sa* and *Ga*), scour fills (*Sl*), plane beds (*Sh*) and gravel dunes (*Gt*). Common lag gravels indicate abundant reworking. This facies assemblage and its depositional environment are similar to the Platte model of Miall (1982) where sedimentation occurs in exceptionally broad shallow rivers, which lack well-defined topographic differences between active and inactive areas.

Facies association 4 (FA 4): This is dominated by low-angle cross-bedded sandstone (*Sl*), and high-angle planar cross-bedded sandstone (*Sp*) in thin to very thick units. Laminated and trough cross-bedded sandstone (*Sh* and *St*), cross-bedded conglomerate (*Gp* and *Gt*), and shale are minor. Cycles or sequences are not discernable. This association occurs in the Galloping Creek Formation near the junction of Smoke Creek and Flying Fox Creek.

Facies association 4 was probably deposited in broad, shallow rivers under high-energy conditions. Bed forms were mainly scour fills or antidunes (*Sl*) and sandwaves (*Sp*), with lesser plane beds (*Sh*), and sinuous dunes (*St*).

Facies *Sl* and *Sh* indicate high flow velocities (Harms and others, 1982), and this association was probably deposited by sheetfloods. This facies association is a high-energy variant of the Platte model, mentioned previously. It bears some resemblance to the Bijou Creek model (Miall, 1982), where deposition occurs during infrequent, violent, flash floods in ephemeral rivers.

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Figure 59. Laminated sandstone at the top of a fining-up sequence (△1) has been eroded, then overlain by trough cross-bedded sandstone at the base of another fining-up sequence (△2). FA 5, Abney Sandstone, Dillon Spring Outlier.

Facies association 5 (FA 5): This consists mainly of trough cross-bedded sandstone (*St*), with minor parallel-bedded sandstone (*Sa*), and rare planar cross-bedded, laminated, and rippled sandstone (*Sp, Sh*, and *Sr*). The association occurs in the upper part of the Abney Sandstone at Dillon Spring and may be up to 150 m thick. Fining-up cycles 2–3 m thick are common. From an eroded base, cycles pass from facies *St* into facies *Sh* and *Sr* (Fig. 59). Climbing ripples may be present. Larger scale cycles have not been observed.

The eroded base to fining-up cycles and dominance of sinuous dunes (facies *St*) suggest FA 5 was deposited in deep channels. Minor bed forms include plane beds (*Sa* and *Sh*), with rare sandwaves (*Sp*) and ripples (*Sr*). This association is similar to the South Saskatchewan model (Miall, 1982; Cant, 1982) where fining-up sequences are generated by both channel aggradation and growth of sand flats. The dominance of facies *St* in FA 5 indicates that the cycles were generated by channel aggradation (Cant, 1982).

Facies association 6 (Fa 6): This consists of fining-up cycles, 7–15 m thick, of parallel and cross-bedded conglomerate (*Ga, Gt*, and *Gp*) at the base, with laminated and cross-bedded sandstone (*Sh, St*, and *Sp*) tops. It occurs in the basal conglomerate unit, 25 m thick, of the Glass Hill Sandstone. From Bungle Bungle outcamp the proportion of conglomerate and size of clasts decrease to the south and east.

Facies association 6 was probably deposited in a high-energy, deep-channel environment. The large scale of fining-up cycles indicates that they were formed by channel aggradation or abandonment. High-energy bed forms developed in deeper parts of the channel and included longitudinal and transverse gravel bars (*Ga* and *Gp*) and channel fills (*Gt*). Sand facies were probably deposited in shallower parts of the channel as plane beds (*Sh*), sandwaves, and dunes (*Sp* and *St*). This association is similar to facies association 2 in alluvial sediments (see above) and to the Donjek model of Miall (1982).

Synthesis

Lower Frasnian sedimentation in the Bonaparte Basin occurred in broad and shallow braided rivers (FA 3, Cyril Sandstone). In the Ord Basin, sedimentation was initially in well-defined deep channels (FA 6), followed by deposition in broad shallow rivers (FA 3, Glass Hill Sandstone). The gradational relationship between FA 6 and FA

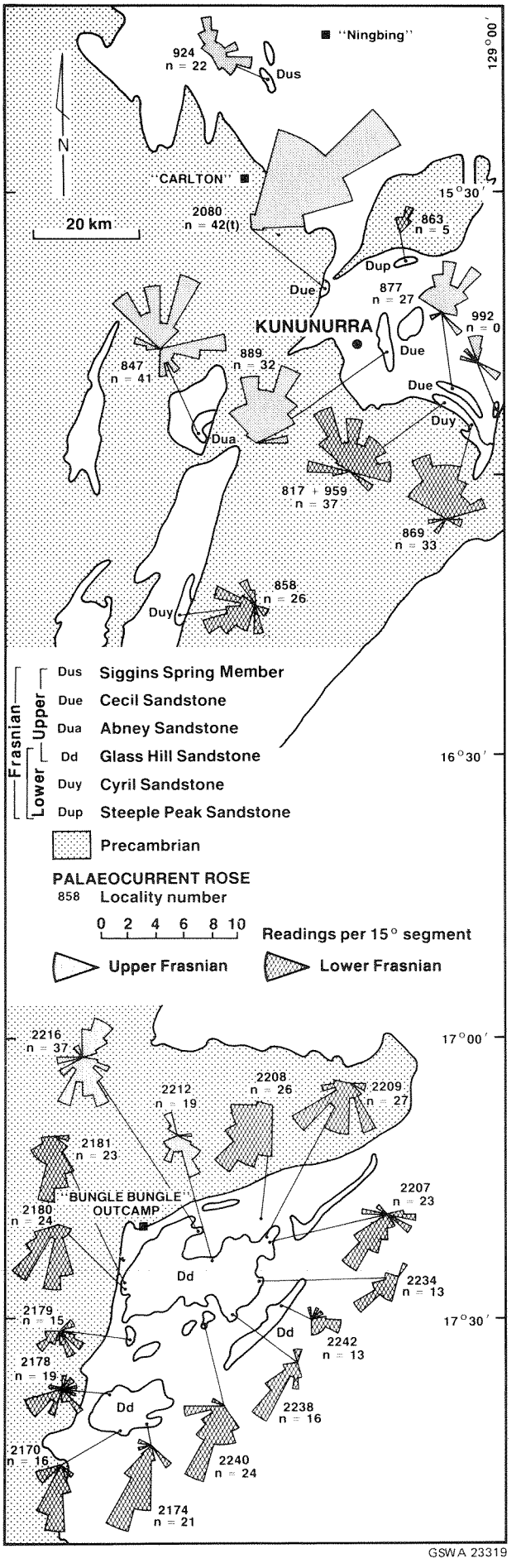

Figure 60. Fluvial sediments; outcrop and palaeocurrent distribution.

3 defines a fining-up megasequence, about 300 m thick. Thick fining-up megasequences indicate erosion of the hinterland (Heward, 1978); the change in braided-river style from channelled (FA 6) to unconfined (FA 3) accompanied this erosion. Transport in the Bonaparte Basin was to the west, at Ragged Range, and to the north at Matheson Ridge (Fig. 60). In the Ord Basin most data were collected from lower parts of the sequence, and the stratigraphically highest positions (location 2216, 2212) are probably in the upper Frasnian. Transport was to the south-southwest and south, coincident with the decreasing amount of conglomerate and clast size in FA 6. Where braided streams interfinger with alluvial environments in the Bonaparte Basin, palaeocurrent directions are similar, indicating that streams flowed on braid plains, distally from alluvial environments.

Upper Frasnian sedimentation occurred in broad and shallow braided rivers (FA 3) in both the Bonaparte Basin (Cecil Sandstone, Siggins Spring Member) and Ord Basin (Glass Hill Sandstone). Deposition in deeper channels (FA 5) occurred in the area of Ragged Range–Dillon Spring (Abney Sandstone), and high-energy, shallow, sheet-flood deposition (FA 4) occurred at southern Ragged Range (Galloping Creek Formation). Transport was to the north and northeast in the Bonaparte Basin and to the south-southeast in the Ord Basin. Palaeocurrent directions in both basins are subparallel or oblique to alluvial directions, suggesting that braided rivers formed on braid plains and axial trunk systems (Rust, 1979).

EOLIAN

Eolian facies occur mainly in the Kellys Knob, Maudoobar, and Purralili Sandstones. Other minor occurrences are near the base of the Ragged Range Conglomerate, (Locality 2095, Fig. 58), in undifferentiated Cockatoo Group in the Mount Rob–Gap Point Outlier (Locality 525, Fig. 64), and in the Glass Hill Sandstone at Dixon Range. Eolian facies are characterized by uniform, fine- to medium-grained sandstone, which is well to very well sorted. Well-rounded and frosted grains are common. Four facies (Table 6), in two facies associations, have been recognized.

TABLE 6. EOLIAN FACIES, COCKATOO AND MAHONY GROUPS

	FACIES	*KELLYS KNOB SANDSTONE (FA 3 is 320 m max)*	*PURRALILI SANDSTONE (FA 3 is 100 m approx., FA 4 is 40 m approx.)*	*MAUDOOBAR SANDSTONE (FA 3 is 400 m max)*
Sp	planar cross-bedded	Sets 0.3–3 m common, range 0.1–8 m, exceptionally >12 m; mainly wedge-shaped bodies, minor tabular bodies; bounding surfaces: scooped, planar, undulating, foresets: max. dip 21°, mainly laminated, minor massive, rare normal grading; bottomsets: minor climbing and reactivated ripples; contortion locally common: overturning, recumbent folds, complex contortions, diapirs (<2 m diameter), faulting.	Sets 0.3–5 m; tabular bodies, minor wedge-shaped bodies; bounding surfaces: planar, undulating; foresets: max dip 30°, laminated, massive <10 cm thick; discordant wedges of foresets along some thick horizons; minor contortion, oversteepened tops; rare thinning-upward sequences up to 8m thick	As for Kellys Knob Sandstone, mainly wedge-shaped bodies; sets <4 m
Sa	parallel bedded and laminated	Minor; medium to thick beds (0.3–0.5 m); rare granule lags, irregular warty lamination	Minor; thick beds <2m; warty lamination; minor ripples, symmetric and strongly asymmetric; mudcrack infill, small channels	Minor; medium to thick beds (0.3—0.5 m); local barite rosettes and contortion
Sl	low-angle cross-bedded	Minor; medium to thick beds (0.1–2.0 m); foresets: planar, scooped, undulating, laminated; rare intraformational breccias	Common; medium to very thick beds (0.3–3 m) erosive base; foresets: max dip 9°, undulating, planar, laminated and massive	—
Sm	massive	—	Shallow channels, max 10 m wide, 2 m deep, steep sided, massive infill; intraclasts: rounded, <60 cm diameter, laminated	—

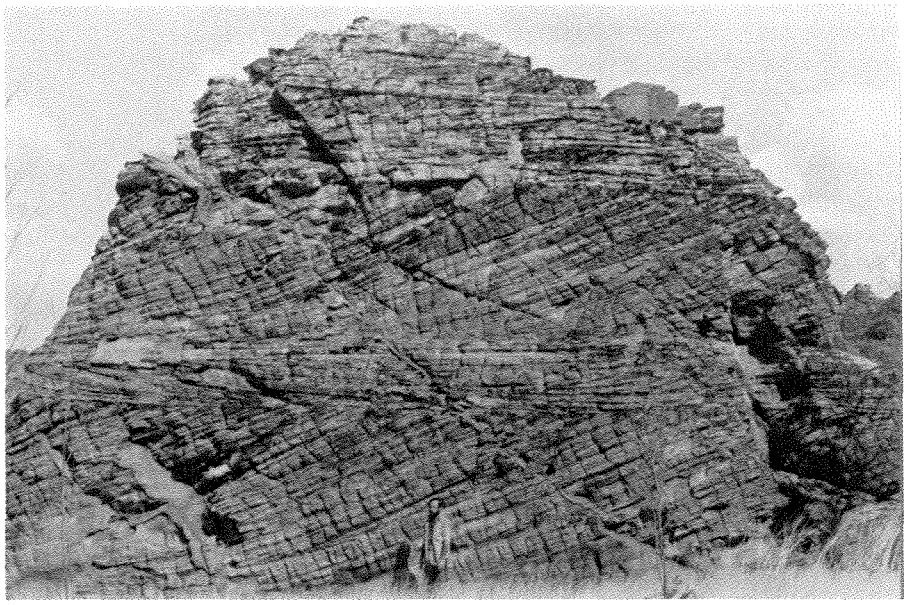

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Figure 61. **Large-scale tabular planar cross-bedding (*Sp*) and low-angle cross-bedding (*Sl*) in eolian FA 7. The lowest planar cross-bed set is about 3.5 m high and foresets have asymptotic bases. Purralili Sandstone, 9 km south-southwest of Mount Mahony (east Bungle Bungle Range).**

Facies

Planar cross-bedded sandstone (*Sp*) consists of high-angle foresets in tabular or wedge-shaped bodies (Figs 61 and 62), controlled by planar, undulating, and scooped bounding surfaces which are either parallel or intersecting. Sets are generally less than 5 m thick, although sets greater than 15 m thick occur in the west Hargreaves Hills (Veevers, 1969; Fig. 6). Thinning-upward sequences (Fig. 63) are rare.

In the lower Frasnian, palaeocurrents (Fig. 64) indicate that transport was to the north and northeast in the Ord Basin (Purralili Sandstone), while in the Bonaparte Basin transport was towards the north and west (Kellys Knob Sandstone). In the upper Frasnian, transport was to the southwest and west (Maudoobar Sandstone). The palaeocurrent pattern from undifferentiated Cockatoo Group in the Mount Rob–Gap Point

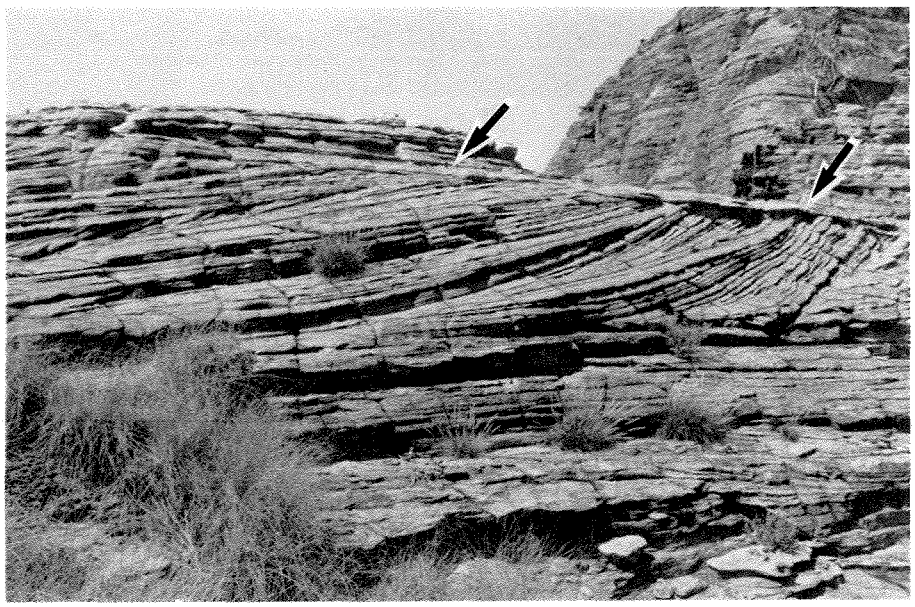

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Figure 62. **Tabular planar cross-bed set overlying parallel-bedded sandstone. The cross-bed set contains discordant intraset wedges (boundaries arrowed) and is about 2.5 m thick. Foresets are characteristically laminated. Purralili Sandstone, 6 km south-southwest of Mount Mahony (east Bungle Bungle Range).**

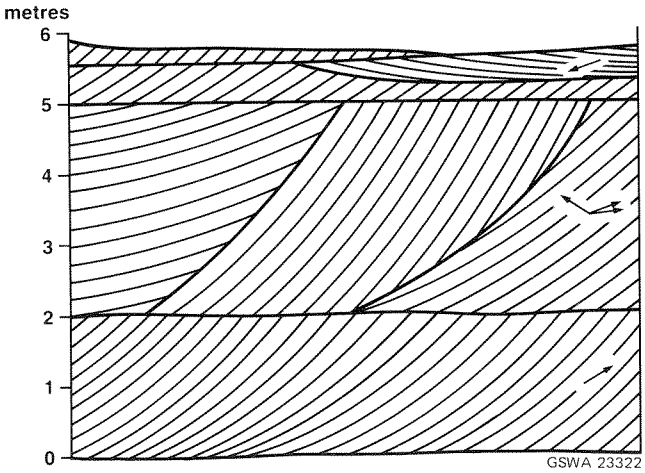

Figure 63. **Thinning-upward sequence of eolian planar cross-beds. The second set consists of overlapping intraset wedges, and a thick foreset in the upper part of the sequence dips up-palaeowind. Purralili Sandstone, 9 km south-southwest of Mount Mahony. Field sketch. Arrows indicate palaeocurrent azimuths.**

Outlier is similar to that in the Maudoobar Sandstone, suggesting it is upper Frasnian.

Facies *Sp* is interpreted as eolian dunes. This is based on texture, size, geometry and the internal fabric of foresets. Well-defined laminae are similar to subcritically climbing, translatent strata, which are formed by wind ripples and are unique to eolian deposits (Hunter, 1977; Kocurek and Dott, 1981). Poorly defined laminae and massive foresets are probably grainfall strata and sandflow cross-strata, respectively (Hunter, 1977). Grainfall deposition is caused by flow separation at the brink of a dune, and sandflow cross-strata form by avalanching of the upper parts of a slipface (Hunter, 1977). Neither are unique to subaerial deposits. Climbing ripples with preserved foresets resemble supercritically climbing translatent strata which normally form on 10° to 25° depositional slopes. Intraset wedges — slightly discordant packets of foresets within a set (Ross, 1933) — indicate overlapping deposition from different parts of a sinuous crested slipface.

Modern barchanoid dunes consist of stacked sets of cross-strata, so that dune height is several times the set thickness, and sets may thin upwards and topsets dip upwind (McKee, 1979; Ahlbrandt and Fryberger, 1982). The thinning-up sequence in the Purralili Sandstone may represent a complete fossil dune, with the top represented by a cross-set with a reverse palaeocurrent direction. As with modern dunes, the height (6–8 m) was at least twice the maximum thickness (3 m). Set thicknesses exceeding 15 m, elsewhere, suggest that the dunes were possibly up to several tens of metres high.

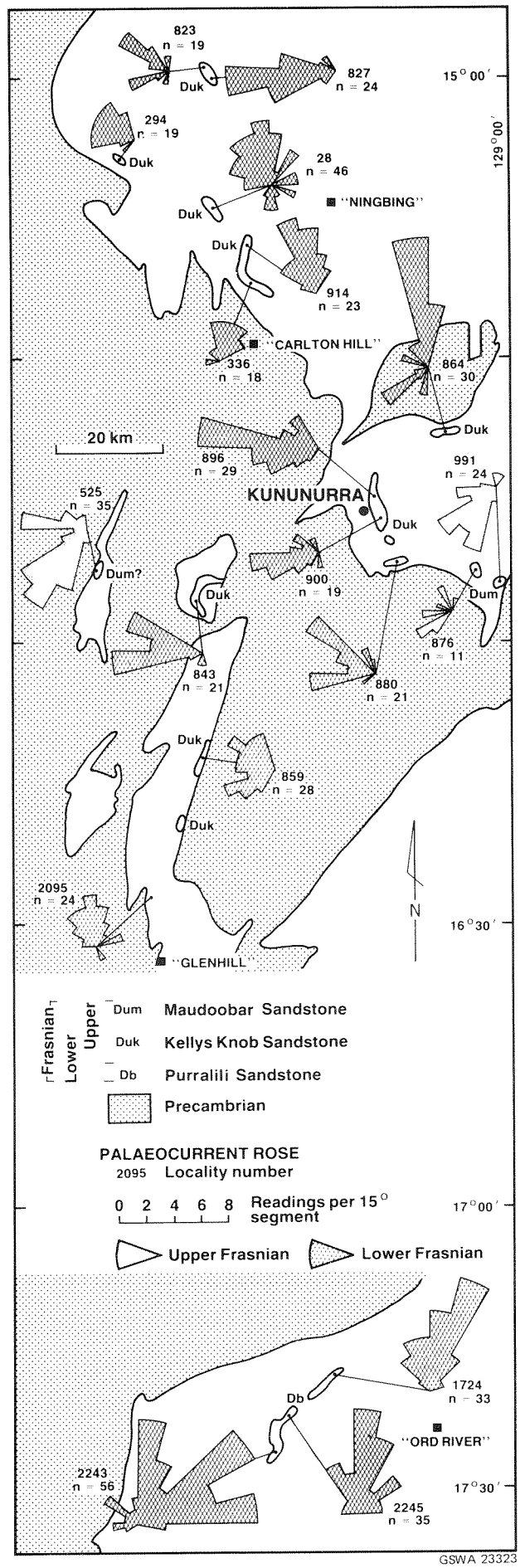

Figure 64. **Eolian sediments; outcrop and palaeocurrent distribution.**

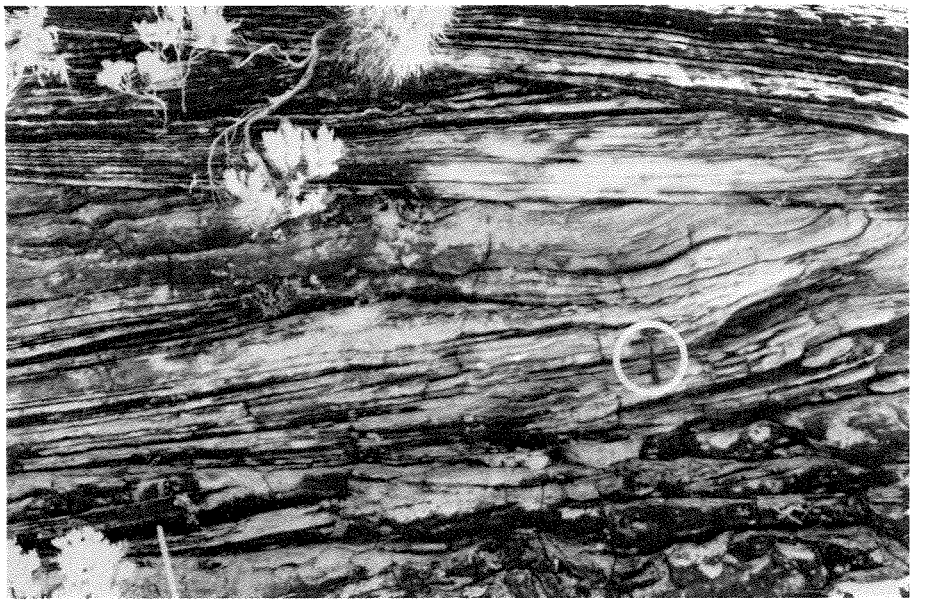

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Figure 65. Low-angle cross-bedded sandstone (facies *Sl*). Foreset lamination has been destroyed by the buckling of bedding. Kellys Knob Sandstone, 1 km east of Kellys Knob (hammer circled).

Palaeocurrent distributions can be used to determine the dune type (Ahlbrandt and Fryberger, 1982). In the lower Frasnian most distributions are wide-unimodal, indicating the dunes were barchanoid ridges. By comparison most upper Frasnian distributions are acute-bimodal indicating these dunes were longitudinal.

Low-angle cross-bedded sandstone (*Sl*, Fig. 65) has foreset structures similar to those in facies *Sp*, although laminae reach 1 cm in thickness. Sets have eroded bases and may pass laterally into facies *Sp* in the Purralili Sandstone. Veevers (1969, p. 16) recorded an intraformational breccia from this facies in the Kellys Knob Sandstone. Clasts in such breccias are up to 1 m diameter and consist of laminated sandstone.

The transitional relationship of facies *Sl* with *Sp* and their similar internal foreset structures suggest that *Sl* represents the bottomsets of high-angle dunes. Higher parts of the foresets were probably removed by erosion. In FA 8, facies *Sl* is much more abundant than facies *Sp* suggesting either deep erosion was common, or facies *Sl* also represents dunes with low-angle slipfaces. Intraformational breccias possibly formed by the collapse of high-angle slipfaces which were moist and cohesive.

Parallel-bedded sandstone (*Sa*) contains some parallel lamination and irregular, warty lamination. It occurs mainly in FA 8 in the Purralili Sandstone. Minor structures include ripples, mudcracks, and small channels. Where granules are present, they have an even distribution on bedding planes. At Cockatoo Fault (locality 991) barite rosettes and plates (up to 2 cm diameter) are concentrated in this facies, although they are also present in facies *Sp*. Deformation and truncation of the folds by overlying bed forms (Fig. 66) indicate that both the deformation and the rosettes formed early. Gypsum commonly forms syndepositionally as an evaporite, and the barite may be a later pseudomorph.

Facies *Sa* probably represents interdune deposits. Parallel lamination and granule lags, with even grain spacing, are characteristic of dry interdune areas (Kocurek, 1981; Ahlbrandt and Fryberger, 1982). Irregular warty lamination possibly represents adhesion ripples formed on slightly moist surfaces. Ripples and channels indicate wave generation in standing bodies of water and current action. Desiccation is indicated by mudcracks and probable evaporites.

Massive sandstone (*Sm*) fills broad shallow channels that tend to occur in distinct horizons in both facies *Sa* and *Sl*. The channels may be steep sided, and the infill includes scattered rounded sandstone intraclasts (Fig. 67) which retain relic bedding structures.

Facies *Sm* probably represents interdune overflow channels formed during major flood periods. Wet conditions are needed to maintain steep channel sides and to form large intraformational clasts in otherwise unconsolidated sand. The internal fabric and size

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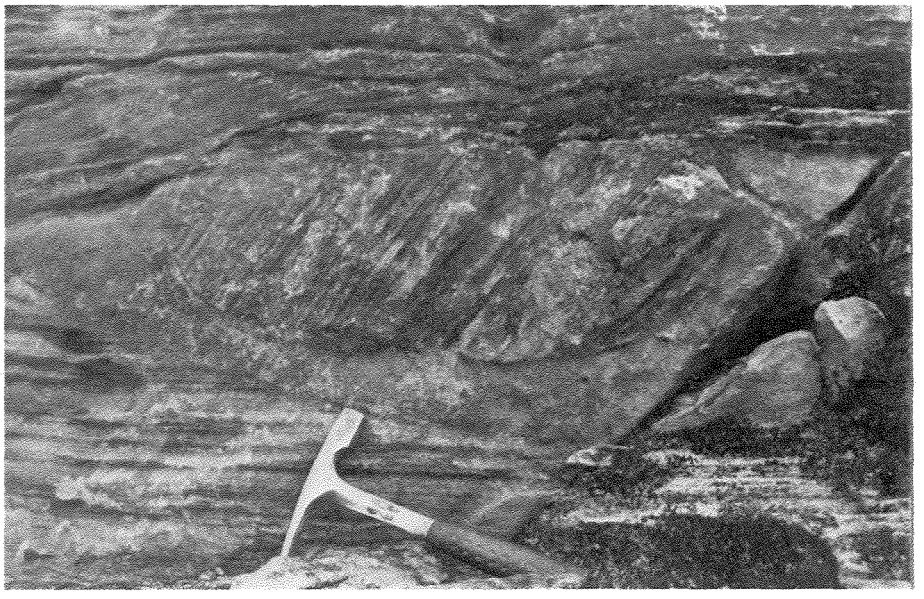
Figure 66. Parallel-bedded sandstone (facies *Sa*) containing barite rosettes (arrowed) which has been folded and truncated (top right of photo). Maudoobar Sandstone, 0.8 km east of the type section.

of the intraclasts indicate that they were probably derived by bank collapse and underwent minimal transport. Rapid deposition of the matrix is suggested by lack of traction-related structures. The restriction of the channels to distinct horizons suggests that they formed during major flood periods. Kocurek (1981) has noted the presence of similar short-lived interdune overflow channels in modern sediments in Padre Island, Texas.

Facies associations

Facies association 7 (FA 7): This association dominates the Kellys Knob and Maudoobar Sandstones, and occurs in the lower 100 m of the Purralili Sandstone. It consists mainly of facies *Sp* with minor *Sa* and *Sl*. Deformation occurs, in both facies *Sp* and *Sa*, and is locally common. Many structures have been truncated by overlying bed



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ıre 67. Truncated intraclast of laminated sandstone in a shallow channel eroded into parallel-bedded sandstone (facies *Sa*). Purralili Sandstone, 16 km south-southwest of Mount Mahony.

forms indicating early periods of generation. Deposition was mainly as dunes (*Sp*) with minor interdune deposits (*Sa*). Facies *Sl* was formed either by deep truncation of high-angle foresets or as low-angle dunes. Palaeocurrent distributions indicate the dunes were mainly barchanoid ridges in the lower Frasnian Kellys Knob Sandstone and longitudinal dunes in the upper Frasnian Maudoobar Sandstone. Dune height varied from several metres to several tens of metres. Granule lags, adhesion ripples and evaporites indicate the interdunes were mainly dry. Deformation is aided by water-saturated conditions, suggesting formation beneath the water table, and is caused by mechanical loading due to the passage of dunes or to seismicity (Doe and Dott, 1980). After deformation strong deflation caused erosion to the water table, exposing and truncating the structures.

Facies association 8 (FA 8): This consists of facies *Sa, Sm,* and *Sl* with minor *Sp.* It occurs above FA 7 in the Purralili Sanstone and is 40 m thick. Deposition occurred mainly as interdunes (*Sa*), low-angle dunes or bottomsets of truncated high-angle dunes (*Sl*), overflow channels (*Sm*), and minor high-angle dunes (*Sp*). Ripples and channels indicate that the interdunes were wet. FA 8 occurs between eolian dunes (FA 7) below and fluvial deposits (FA 3, Glass Hill Sandstone) above, and it shows influences of both. Similar transitional deposits between eolian and non-eolian environments have been termed sand-sheet deposits (Fryberger and others, 1979).

DELTAIC AND SHALLOW MARINE

Deltaic and shallow-marine environments occur in the Hargreaves Formation in the Burt Range and Carlton Shelves. A number of facies are present (Table 7) and, based on the relative abundance of sandstone or dolomite, the sequence is divided into two facies associations (FA 9 and FA 10) illustrated in Figure 68.

Fossils and glauconite, in most of the sandstone and shale facies, indicate a shallow-marine depositional environment. Grain size and bedding structures in facies *Sa* and *Sh* indicate high-energy traction deposition (Harms and others, 1982; p. 246). Lower energy periods indicated by ripples, siltstone beds, and bioturbated bedding planes suggest that facies *Sa* and *Sh* were deposited in a

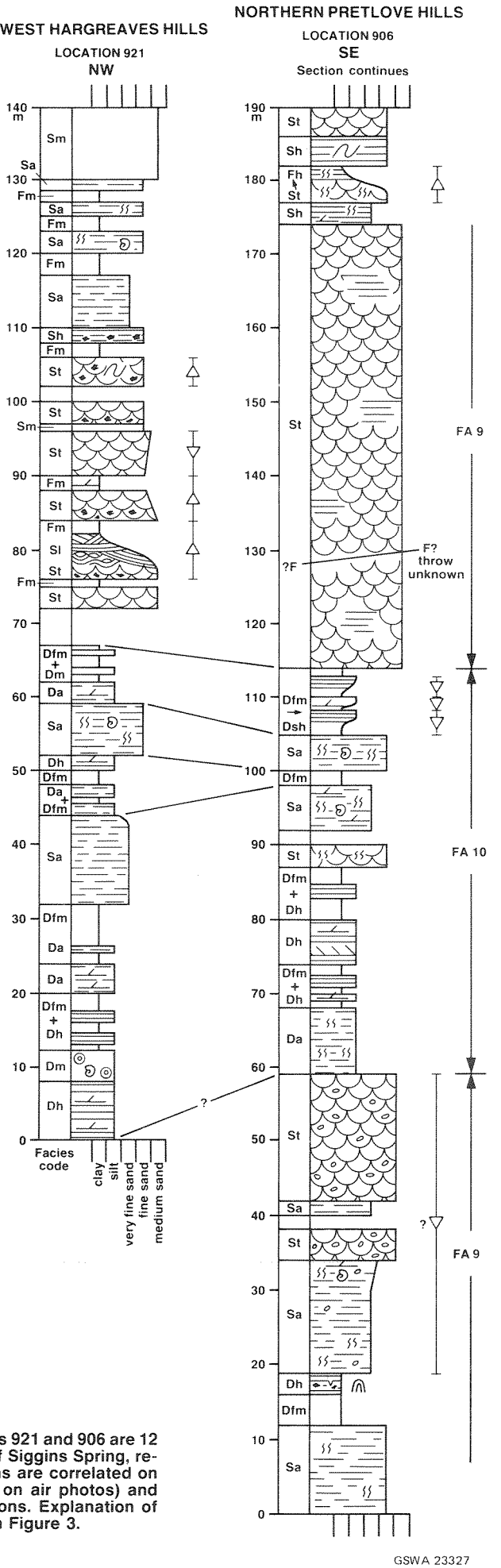

Figure 68. Hargreaves Formation measured sections. Sections 921 and 906 are 12 km west-southwest and 12 km south-southwest of Siggins Spring, respectively, and are about 8 km apart. The sections are correlated on their similar stratigraphic positions (traced beds on air photos) and similar sequences of facies and facies associations. Explanation of facies codes in Tables 1 and 8, key to symbols in Figure 3.

TABLE 7. DELTAIC AND SHALLOW-MARINE FACIES, COCKATOO GROUP

Facies		*Description*	*Bed thickness*	
			FA 9	*FA 10*
SANDSTONE:				
St	trough cross-bedded	Common; fine to med. grained, well sorted, reworked mud intraclasts, scattered granules and pebbles, glauconitic; mainly medium sets (0.3 m), range 0.1–0.5 m; minor ripples, medium parallel bedding; rare local subvertical burrows; some coarsening (thickening)-up, and fining-up sequences	5 m (av.) 2–60 m (range)	4 m (av.) 2–5 (range)
Sa	parallel-bedded	Common; v. fine to fine grained, well sorted, rare pebbles and mud intraclasts; minor lamination, interference and longitudinal ripples, and medium to thick siltstone beds; locally strongly bioturbated, body fossils unfragmented	5 m (av.) 2–12 m	4 m (av.) 1–8 m
Sm	massive	Minor; fine to med. grained; minor contorted cross-bedding	0.5 m	4 m (av.) 2–6 m
Sh	laminated	Rare; fine grained; scattered mud intraclasts; bioturbated	2 m (av.)	—
Sl	low-angle cross-bedded	Rare; fine to med. grained; transitional with *Sa;* fines upwards into shale	5 m	—
SHALE:				
Dh	laminated (a)	Common; minor breccia, ripples	2 m	2 m (av.) 1–5 m
Da	parallel bedded (a)	Common; thin bedded; minor ripples, thin trough cross-beds, shale beds, and bioturbation; rare breccia	—	3 m (av.) 1–8 m
Db	brecciated (a)	Minor; laminated intraclasts <12 cm (max)	—	0.1–0.2 (av.)
Dm	massive (a)	Common; minor breccias, very thin shale beds, oncolites, beds of articulated and disarticulated body fossils	—	3 m (av.) 1–10 m
Df	massive (b)	Common; *minor Dh* and *Ds* interbeds or caps to coarsening-up cycles 0.4 m thick	3 m	3 m (av.) 1–8 m
Ds	stromatolitic	Rare; simple, linked, undulating laminae	—	0–2 m (max.)
SILTSTONE/SHALE:				
Fr	rippled	Rare; longitudinal ripples, minor bioturbation	1.5 m	—
Fm	massive	Common	2 m (av.) 0.5–3 m	1 (av.) 0.5–2 m

(a) dolomite: may be sandy

(b) dolomite: shaly

shoreface environment (McCubbin, 1982). Grain size in massive sandstone (*Sm*) indicates high-energy shoreface deposition. The massive nature may be caused by: deformation (fluidization) as indicated by minor contorted cross-beds; rapid deposition so that structures cannot develop; or complete bioturbation. Facies *Fm* and *Fr* indicate quiet-water suspension deposition, and were deposited in lagoonal or offshore environments. Facies *St* was deposited in several high-energy environments. Thick sequences (to 60 m) lacking bioturbation or body fossils are probably fluvial deposits. The Siggins Spring Member, a very thick lens (190 m) of this facies, is also believed to be fluvial.

Thinner bioturbated units forming fining-up sequences with marine facies possibly represent tidal channels or, given the presence of fluvial channels, may be abandoned distributary channels. Facies *Sl* occurs only within a fining-up sequence between facies *St* and *Fm* (above), and represents the shallower part of a channel.

Intraformational breccia (*Db*), laminated dolomite (*Dh*, Fig. 69), and stromatolitic dolomite (*Ds*) in the dolomite facies probably represent storm deposition, microbial lamination, and stromatolites, respectively. These distinctive facies indicate deposition in supratidal and intertidal environments (Shinn, 1983). Parallel-bedded dolomite (*Da*) is similar to facies (*Sa*) and may also represent subtidal shoreface deposition. Small dunes on the shoreface probably formed through cross-bedded units. Massive dolomites (*Df* and *Dm*) were deposited in a low-energy lagoonal environment, which was interrupted by high-energy periods producing breccia and disarticulated body fossils. Intertidal and supratidal dolomites, capping coarsening-up sequences in lagoonal sediments, indicate periodic shoaling.

Facies associations

Facies association 9 (FA 9): This association forms outcrops in both the Carlton and Burt Range Shelves. It consists of up to a few hundred metres of sandstone with isolated dolomite beds up to 6m thick. Major facies are trough cross-bedded and parallel-bedded sandstone (*St* and *Sa*) and massive shale (*Fm*). Minor facies include laminated, massive, and low-angle cross-bedded sandstone (*Sh*, *Sm*, and *Sl*). Rippled siltstone (*Fr*), laminated, and parallel-bedded dolomite (*Dh* and *Da*) and massive dolomitic shale (*Df*) are rare. Thick non-bioturbated facies *St* in this association (section 906) is probably laterally equivalent to several, thinner, fining-up cycles (section 921, Fig. 68). Near the base of section 906, facies *St* overlies *Sa* in a coarsening-up cycle, 40 m thick.

Deposition occurred in fluvial, distributary, and tidal channels (*St* and *Sl*), shoreface environments (*Sa*, *Da*, *Sh*, and *Sm*) and offshore or lagoonal environments (*Fm*, *Fr*, and *Df*). Intertidal dolomites (*Dh*) are rare. The mix of fluvial and tidally influenced shallow-marine deposits suggests that this association represents a tidally influenced delta and that deposition occurred on the delta plain (Coleman and Prior, 1982). The

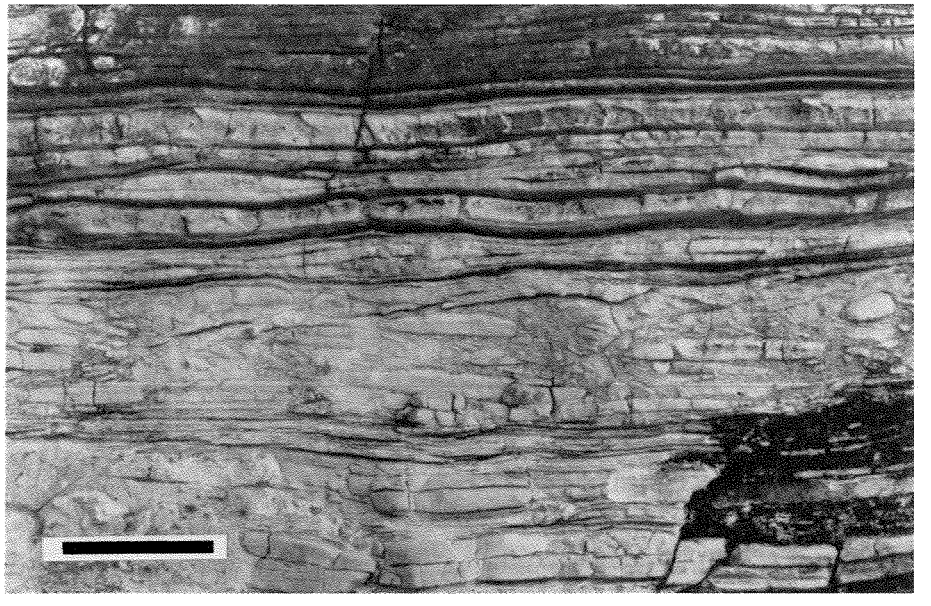

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Figure 69. Laminated dolomite (facies *Dh*) with a bed of intraclast breccia. Imbrication in the smaller intraclasts indicates palaeocurrents flowed to the left. Hargreaves Formation, northern Pretlove Hills. Scale bar is 10 cm.

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palaeoshoreline was oriented northwest-southeast, as indicated by fluvial palaeocurrents in the very thick fluvial deposits (Siggins Spring Member, Figure 60, section 924). This shoreline orientation shows that the lateral transition between thick fluvial (*St*) and thinner fining-up distributary environments, in sections 921 and 906, occurred along depositional strike. The coarsening-up sequence in section 906 represents progradation of a fluvial lobe over shoreface deposits.

Facies association 10 (FA 10): This occurs only in the Carlton Shelf, mainly in the Pretlove and Hargreaves Hills. It is up to 100 m thick and consists of several units of sandy and silty dolomite (up to 32 m thick) separated by thinner sandstones (Fig. 68). In the west Hargreaves Hills, dolomites are up to 44 m thick. Laminated dolomite (*Dh*) and massive shaly dolomite (*Df*) are dominant, with lesser massive and parallel-bedded dolomite (*Dm* and *Da*), and parallel-bedded sandstone (*Sa*). Minor facies include massive and bioturbated trough cross-bedded sandstone (*Sm* and *St*) and massive shale (*Fm.*) Brecciated dolomite (*Db*), stromatolitic dolomite (*Ds*) and laminated sandstone (*Sh*) are rare. Massive sandstones are more common and have a greater thickness than in FA 9. Dolomite facies are laterally persistent over 8 km, and facies *St* is transitional with facies *Sa.*

Assuming a related setting to FA 9, this association was probably deposited on a subaqueous delta plain. Intertidal-supratidal facies (*Dh, Db,* and *Ds*) and lagoonal facies (*Dm, Df,* and *Fm*) were laterally persistent over at least 8 km of depositional strike, and were probably deposited in interdistributary bays. Coarsening-up shoaling cycles may represent progradational crevasse splays. Tidal and/or distributary channels (*St*) and shoreface deposits (*Sa, Da,* and *Sm*) were transitional along depositional strike.

When the measured sections of Hargreaves and Pretlove Hills are correlated, both associations appear as non-transitional separate bodies, and FA 10 could also represent a barrier complex, separate from the deltaic plain. In a barrier complex (McCubbin, 1982) shoreface (*Sa*) and tidal-channel deposits (*St*), represent the subtidal seaward side of the barrier, and tidal-inlet environments, respectively. Intertidal-supratidal and lagoonal deposits possibly formed in a back-barrier environment. Shoaling cycles in the lagoon may represent washover deposits from the barrier. With increasing tidal range (although there is some overlap) tidal flats become more common and barrier islands less common (Elliot, 1978). The abundance of intertidal sediments in FA 10, suggests that barrier islands were unlikely to have been developed, and deposition probably occurred in interdistributary bays of the tidally influenced delta.

TIDAL

Tidal environments occur mainly in the Steeple Peak Sandstone, also in the Abney Sandstone at Kununurra and at Dillon Spring (lower part of the formation). Tidal environments also make up small parts of the Kellys Knob Sandstone (basal 20 m of type section, Alice Hill, and Elephant Hill), Glass Hill Sandstone (basal 10–20 m north of White Mountain), Hargreaves Formation (sporadically, in the northern Pretlove Hills) and the Ragged Range Conglomerate (basal 5–10 m at Conglomerate Hill).

Tidal sediments are characterized by fine- to medium-grained, well-sorted sandstone, locally with scattered coarse sand, granules, and small pebbles. Thick sequences of laminated to thin, parallel-bedded sandstone are dominant (facies *Sh* and *Sa*). Parting lineation may be present on bedding planes. Minor facies include ripples (*Sr*) and low-angle cross-bedding (*Sl*). Ripples include symmetric, asymmetric, longitudinal, interference, and ladder types, and may be washed out and eroded. Rarely the ripples have a mud drape, forming wavy to flaser bedding.

At Kellys Knob several fining-up sequences, 0.3 to 6 m thick, of facies *Sl* to *Sh* (top) occur in a bed, 3 m thick, with each sequence having an eroded base. Thin to medium trough cross-bedding (*St*), mudcracks and contorted beds are rare. Trough cross-beds occur in shallow channels, 10 m wide by 0.5 m deep, or have non-eroded bases, and may include mud intraclasts. Mudcracks vary from 5 cm diameter and 1 cm thick to less than 1 cm diameter and few millimetres deep. Isolated and very rare structures include poorly preserved setulfs and ilots. Body and trace fossils are uncommon, and completely bioturbated beds occur rarely at Dillon Spring.

Pebbly sediments occur locally in the Steeple Peak Sandstone. At the base of the unit, at Steeple Peak, a pebble to boulder conglmerate, 4 m thick, underlies tidal facies. The conglomerate is clast supported, bimodal, massive (*Gm*), planar cross-bedded (*Gp*), and parallel bedded with some imbrication (*Ga*). The top of the bed is sharply defined. At Dillon Spring medium to thick beds of medium cross-bedded pebbly sandstone (*St* and *Sp*) cap coarsening and thickening-up tidal sequences, 10 m thick. The base of each sequence is marked locally by a pebble lag.

The limited data available indicate that palaeocurrent patterns are similar in both upper and lower Frasnian units (Fig. 70). Wave-ripple crests show variations in orientation from west-southwest to northwest, and parting lineations are oriented north–south. Cross-bed palaeocurrent directions are parallel, or slightly oblique, to the ripple-transport directions for each location, generally indicating transport to the north and northeast. At Mount Cecil (location 892) cross-beds indicate southeasterly transport. Imbrication in the conglomerate at Steeple Peak indicates northerly transport.

A tidal-flat environment (Weimar and others, 1982) is indicated by the marine trace and body fossils and the evidence of emergence such as mudcracks, washed-out ripples, setulfs and ilots. Subtidal deposition is dominant, with minor intertidal deposition. Thick beds of fine- to medium-grained facies, *Sh* and *Sa*, indicate high flow velocities (Harms and others, 1982), suggesting deposition in subtidal areas (Weimar and others, 1982). Parting lineations indicate that the currents flowed north–south.

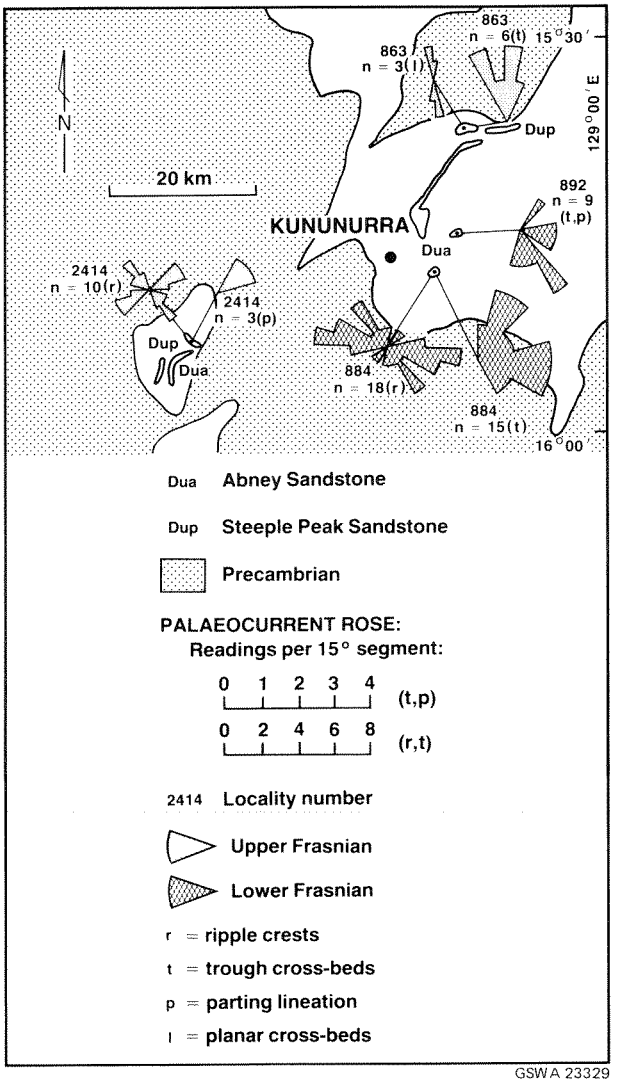

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Figure 70. Tidal sediments; outcrop and palaeocurrent distribution.

Washed-out ripples and superimposed ripples (with variable crest orientation) indicate emergence runoff intertidal deposition (Klein, 1977). Setulfs form by wind erosion of slightly damp or moist sand (Collinson and Thompson, 1982, p. 46). Ilots are island remnants of intertidal flats which are eroded by storm-generated waves during high spring tides (Klein, 1977). Fining-up cycles of facies *Sl* to *Sh* are similar to sequences developed by the lateral migration of small-scale tidal channels on intertidal flats (Weimar and others, 1982) where facies *Sl* and *Sh* represent longitudinal point-bar deposits in the channel and intertidal flats, respectively.

Other structures reflect lower energy deposition and were formed either in subtidal areas, during low-energy periods, or in intertidal areas. Facies *St* was deposited as sinuous-crested dunes in channels or concordant dune fields. The dunes migrated to the north, northeast, and southeast; assuming land was to the south, then ebb-tidal and flood-tidal currents, respectively, were responsible. Mud drapes, flaser bedding, and wavy bedding reflect the alternation of tidal-current bedload deposition with suspension deposition, during slack water (Klein, 1977). Symmetrical ripples are uncommon suggesting little wave action. Waves that were present travelled generally from north to north-northeast.

The pebbly sandstone and conglomerate facies are similar to those in the alluvial environments, and are interpreted to be of fluvial origin. The Steeple Peak Sandstone is laterally equivalent to alluvial sediments (Fig. 52) and the coarsening-up sequences at Dillon Spring were probably caused by migration of fluvial lobes into a tidal environment.

Tidal deposition in the Bonaparte and Ord Basins was mainly in subtidal environments, with minor deposition in intertidal flat and tidal-channel environments. Tidal channels are common in most modern tidal flats, but absent in the Gulf of California (Weimar and others, 1982), suggesting that the latter may be a modern analogue of sequences in the Bonaparte and Ord Basins. In the Gulf of California, deposition in an embayment is controlled mainly by a high rate of sediment input, a low wave energy, and a high tidal range (4–5 m average, 10 m max). Channels are uncommon on the intertidal flat due to the absence of barriers to confine flow, so that tidal currents move over flats as a broad uniform flow (Thompson, 1975). In the Bonaparte and Ord Basins, sequences also show

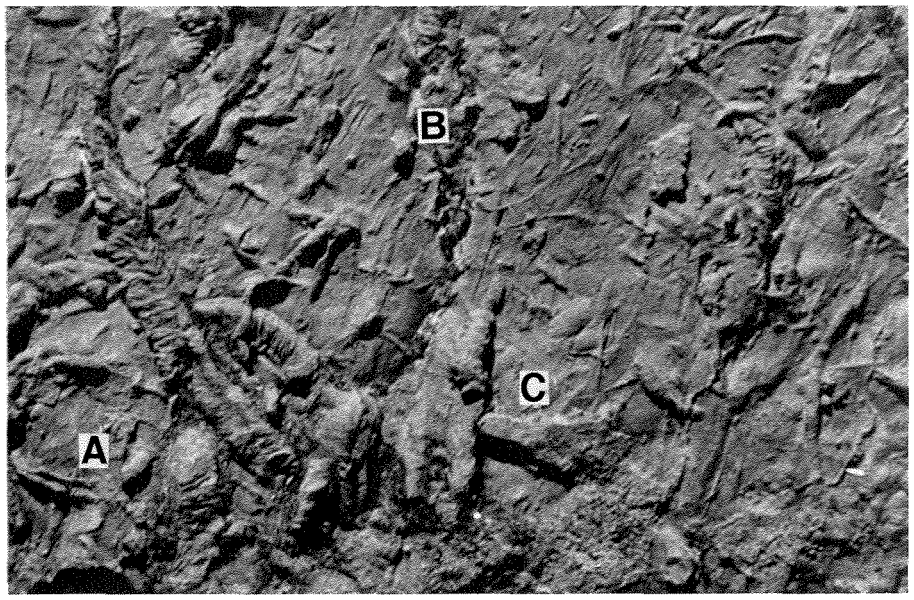

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Figure 71. Small *Cruziana* (A), *Monomorphichnus* (B), *Rusophycus* (C) and other trace fossils on the underside of a sand bed. *Monomorphichnus* are aligned in response to current flow. Kununurra Formation, type section.

some of these controls. Contemporaneous fluvial and alluvial deposition, and interbedded fluvial facies, suggest a high rate of sediment input. Palaeogeographic reconstructions (Fig. 125) also indicate deposition in a narrow gulf. The tidal range cannot be estimated, but it may have been similar to that in the Gulf of California.

SHOREFACE

Shoreface environments occur mainly in the Kununurra Formation and in lenticular bodies in the Hargreaves Formation in eastern Pretlove Hills.

Sediments consist mainly of fine- to very fine-grained glauconitic sandstone, with minor dolomitic sandstone, dolomite, and shale. Thin sandstone and dolomitic sandstone beds are parallel bedded (*Sa*), laminated (*Sh*) and rippled (*Sr*). *Cruziana* occurs on the soles of beds (Fig. 71). Within beds there is bioturbation together with disarticulated and unfragmented body fossils. Sandstone beds are thinner and fossils are more common in the lowest 40 m of the Kununurra Formation type section. North of Kununurra, dolomite beds up to 4 m thick are laminated (*Dh*) or massive (*Dm*). Laminated shales (*Fh*) are probably interbedded with sandstone and occur in thick beds.

Deposition in lower shoreface environments occurs during alternating periods of low and high energy (McCubbin, 1982). Facies *Sh* and *Sa* are high-energy deposits, and *Sr* represents lower energy deposition (Harms and others, 1982). *Fh* and *Dm* represent quiet-water suspension deposition in either lower shoreface or offshore environments. The lamination in dolomites (*Dh*) was possibly formed by subtidal microbial mats. Unfragmented body fossils and subvertical burrows indicate that organisms were smothered by rapid deposition, possibly caused by storms. *Cruziana* are preserved either by sand infilling surface tracks, in underlying muds, or by the collapse of sand into burrows at a sand-mud interface (Basan, 1978).

In the Kununurra Formation type section, the thickening of sandstones and decrease in fossil abundance upwards, reflect increasing energy due to shallowing. The absence of relatively deep-water dolomites in southern sections may also reflect shallowing.

REEF

A reef environment occurs only in the Westwood Member of the Hargreaves Formation, in a restricted area at Westwood Creek. Two interfingering facies are present: massive stromatoporoid-*Renalcis*-stromatolite boundstone (*Cm*) and crudely bedded fossiliferous limestone (*Ca*, Fig. 72). Fossils in facies *Ca* include diverse shelly and microbial material, with large bivalves and oncolites locally abundant. The faunal association in *Cm* clearly indicates it is either a reef-flat or reef-margin environment, and *Ca* is interpreted

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Figure 72. Bivalves with a thin oncolitic coating, Westwood Member (Hargreaves Formation) type section.

as a back reef. The isolated occurrence of the Westwood reef suggests it was a pinnacle or patch reef, and not part of a more extensive Frasnian reef complex.

DEPOSITIONAL ENVIRONMENT

The Cockatoo and Mahony Groups were deposited in two depositional systems. The distribution and relationship of environments, and flow directions are complex (Figs 124 to 126). The lower Frasnian depositional system (Fig. 124) consisted of alluvial-fan, fluvial, eolian, intertidal, and shoreface environments. Streams generally flowed perpendicular to the north-northeast-oriented bounding faults. In the lower part of the upper Frasnian (Fig. 125), the depositional system was similar to that in the lower Frasnian, except stream flow was both perpendicular and parallel to the bounding faults. In the upper part (Fig. 126), the depositional system consisted of fluvial, deltaic, eolian, shallow-marine, and reef environments.

CHAPTER 4

Famennian of the Bonaparte Basin

INTRODUCTION

The first observations on the Famennian carbonates of the Bonaparte Basin were those of Reeves (1949, 1951). It was not until the early 1960s that the Famennian sequence was differentiated from the Tournaisian of the Burt Range area (Veevers and Roberts, 1968). Veevers and Roberts utilized the age determinations of Jones and Druce (1966) and the recognition of facies in a reef-complex, at the southern end of Ningbing Range, by Playford and others (1966) to produce the first detailed maps of the Famennian carbonates (Veevers and Roberts, 1968, Figs 31 and 33). North of Surprise Creek, however, Veevers and Roberts had limited success in delineating facies in the carbonates due to the strongly dissected exposures and dolomitized fabrics.

As with the reef complexes in the Canning Basin (Playford, 1980, Figs 6 and 7) three basic facies are recognized in the reef complex as exposed in the Bonaparte Basin: platform, marginal-slope, and basin facies (Fig. 73). In the Bonaparte Basin carbonates of the platform facies comprise three subfacies: reef-margin, reef-flat, and back-reef. Dipping fore-reef talus deposits, of the marginal-slope facies, flank the elevated platform facies and pass downdip into flat-lying shale and limestone of the basin facies.

The platform facies was deposited in shallow water on a relatively elevated area. At the periphery of the platform there is a massive boundstone reef, generally some tens of metres in width, which forms a wave-resistant zone and is referred to as the reef-margin subfacies. Immediately behind the reef margin is the reef-flat subfacies which, like the reef margin, is composed of microbial boundstone but is crudely bedded. Landwards of the reef flat is the back-reef subfacies consisting of well-bedded lagoonal carbonate deposited in water depths estimated at 5 to 10 m (Playford, 1980).

The marginal-slope facies adjoins the seaward side of the platform facies and shows steep depositional dips which shallow rapidly downdip. In the Bonaparte Basin this facies is dominated by limestone breccia with minor skeletal carbonate.

Adjoining the reef margin, poorly bedded microbial skeletal boundstone (with relatively steep dips) may be present at the top of the marginal slope. These carbonates form the reefal-slope subfacies; the subfacies, however, is not always present and is rare in the Bonaparte Basin. Where talus deposits of the marginal slope can be demonstrated to adjoin a reef margin, they may be referred to as fore-reef subfacies. In the Bonaparte Basin, limestones of the marginal-slope facies often cannot be shown to be associated with a reef margin and so cannot be referred to the fore-reef subfacies.

Down dip from the marginal-slope facies, the basin facies was deposited nearly horizontally. The basin facies consists largely of fine-grained terrigenous sediment with thin beds of pelagic and detrital limestone. In the Canning Basin the basin facies is estimated to lie in water depths of up to 400 m (Playford, 1980). The maximum difference in elevation between basinal and marginal-slope facies, that can be demonstrated in the Bonaparte Basin, is 200 m in the section north of Tanmurra Creek (Plate 3, section CC').

Systematic palaeontological studies of Famennian faunas from the Bonaparte Basin include works on corals (Hill, 1954), ostracods (Jones, 1968; 1985), conodonts (Druce, 1969), calcareous algae (Veevers, 1970; Mamet and Roux, 1983), brachiopods (Roberts, 1971) and miospores (Playford, G., 1982). Fossil groups yet to be described include foraminifers, stromatoporoids, bryozoans, gastropods, crinoids and bivalves. Conodonts, and miospores are the most useful groups in local and inter-regional correlations. Ostracods are at present of doubtful use in local correlations; *e.g.* Playford (1982) demonstrated that the Buttons Formation is latest Famennian, an age which conflicts with Jones' (1968) ostracod-based correlation of the Buttons Formation with the lower, early Famennian, part of the Ningbing Limestone (Djilirri Limestone, this bulletin). While Jones (1985) confirmed the latest

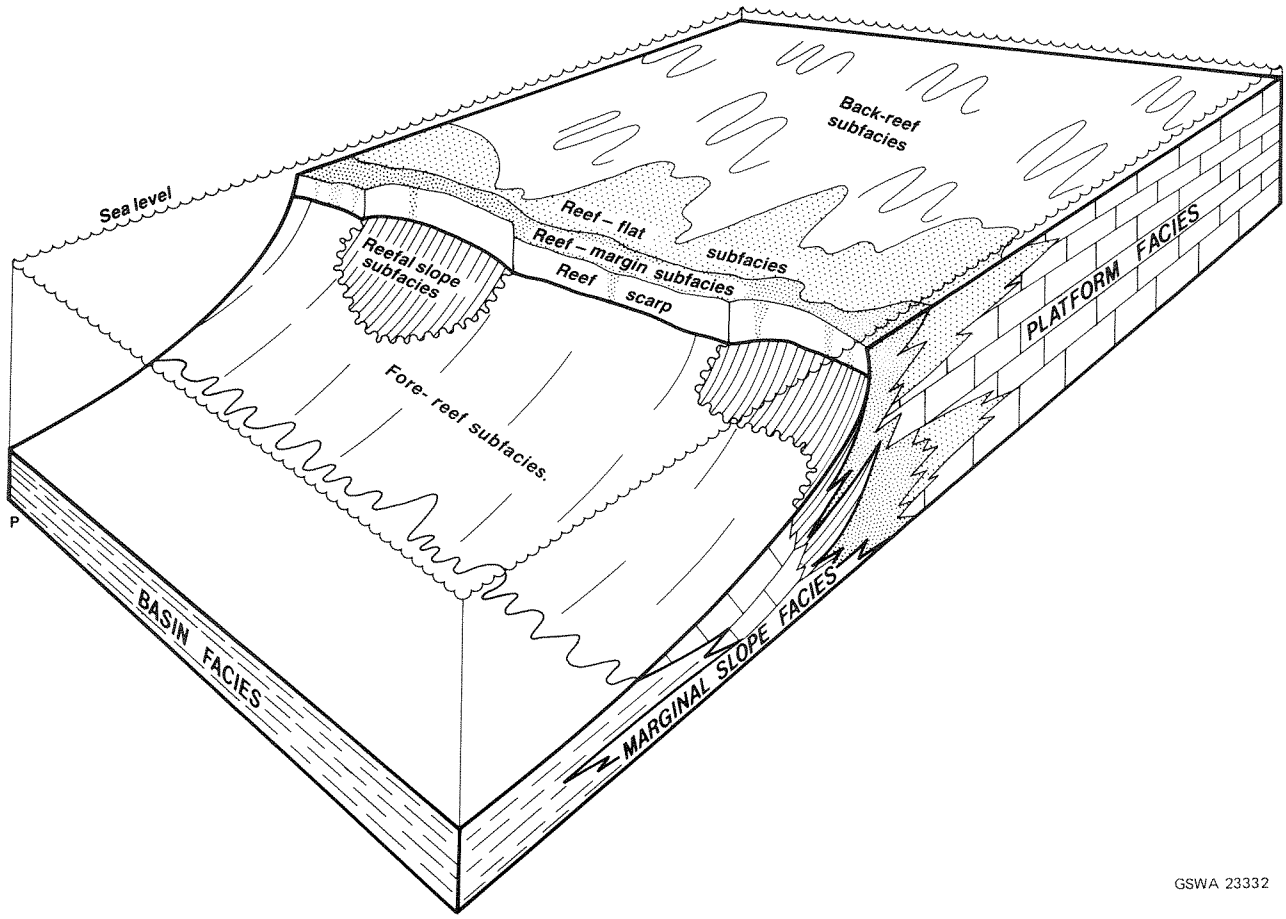

Figure 73. Block diagram illustrating facies and subfacies relations in reef complexes (after Playford, 1980, Figs 6 and 7). Not to scale.

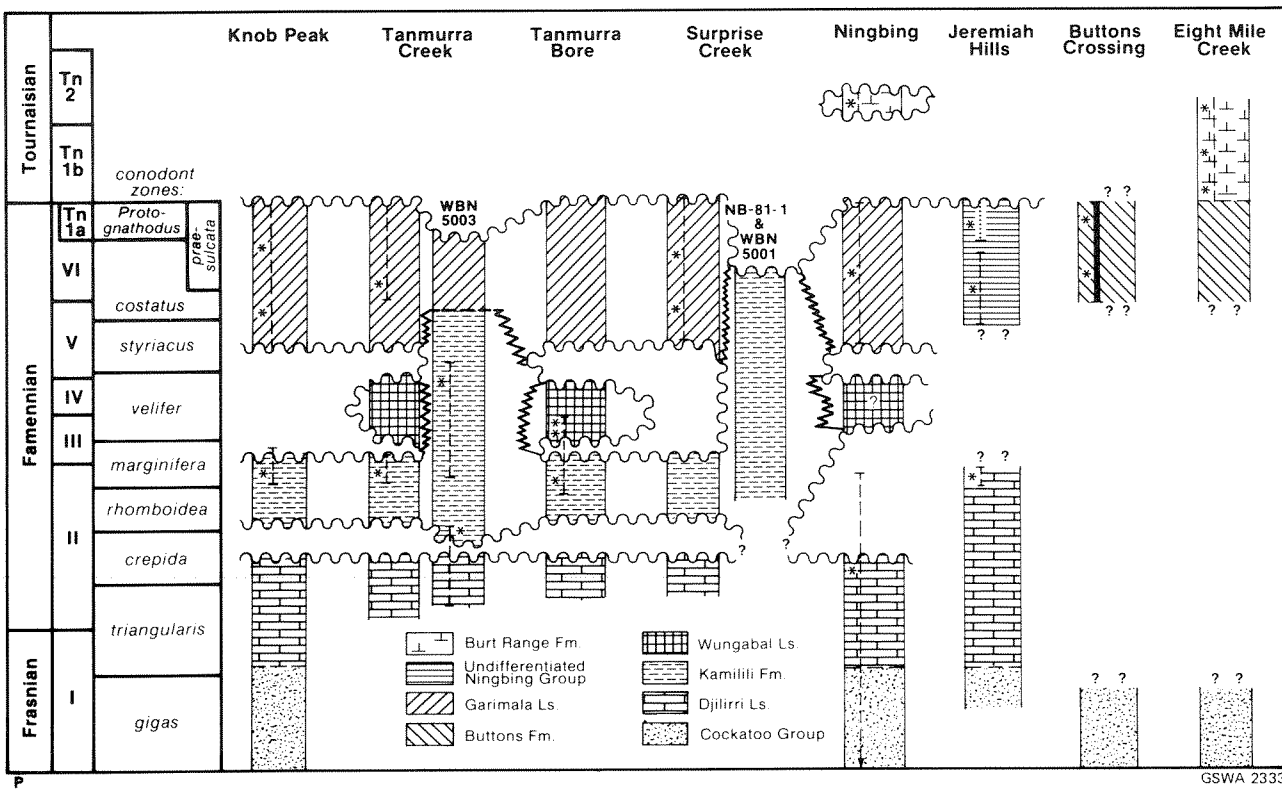

Figure 74. Correlation of principal sections of the Ningbing Group based on conodont faunas (dashed lines — Druce, 1969; R. S. Nicol, 1982, written comm.), miospores (solid line Playford, G., 1982), and stromatoporoids (dotted line — A. E. Cockbain, pers. comm.). Asterisks indicate the units from which ages have been determined. Stratigraphic columns not to scale.

Age		Rock unit (with map symbol)	Thickness (m)	Lithology and depositional environment	Stratigraphic relationships
Famennian	do V-VI	Garimala Limestone (Dug)	150-340	Limestone breccia (marginal slope) and massive microbial limestone (reef margin)	Disconformably overlain by Carboniferous units. In outcrop disconformably overlies Djilirri Limestone, Kamilili Formation or Wungabal Limestone. Basinwards laterally equivalent to Kamilili Formation.
		Buttons Formation (Dub)	350	Well-bedded skeletal limestone (lagoonal — ? back reef)	Equivalent to Garimala Limestone based on age. Contacts in type area obscured. Conformable upper contact with Carboniferous Burt Range Formation in Eight Mile Creek area.
	do IV	Wungabal Limestone (Dul)	0->100	Red 'scheck' breccia (marginal slope)	In outcrop overlain by Garimala Limestone, underlain by Kamilili Formation, both contacts local disconformities. Basinwards probably passes into Kamilili Formation.
	do III	Kamilili Formation (Dui)	160-?750	Flaggy skeletal limestone, shale, mudstone and limestone breccia (marginal slope to basinal)	In outcrop disconformably overlain by Wungabal or Garimala Limestones, disconformably overlies Djilirri Limestone. Basinwards is equivalent to Garimala Limestone, probably Wungabal Limestone and possibly Djilirri Limestone.
	do II	Djilirri Limestone (Dud)	220-400	Well-bedded peloidal limestone (back reef) massive microbial limestone (reef margin) and limestone breccia (marginal slope).	In outcrop disconformably overlain by Kamilili Formation or Garimala Limestone. Conformably overlies Cockatoo Group. Possibly equivalent to Kamilili Formation basinwards.

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Figure 75. Stratigraphic units in the Ningbing Group.

Famennian (Strunian) age of the Buttons Formation he did not comment on this previous correlation. The correlation of principal sections shown in Figure 74 is based primarily on ages determined from conodont faunas. Since these conodont faunas are generally of low diversity, the age determined for a single sample is usually the time range of only one or two species. Consequently the age of specific units has, in some cases, been significantly modified from the conodont ages utilizing evidence from field relationships and lithostratigraphic correlations.

NINGBING GROUP

Famennian carbonates of the Bonaparte Basin, deposited in a reef-complex, are collectively referred to as the Ningbing Group which is equivalent to the "Ningbing Limestone" and "Buttons Beds" of Veevers and Roberts (1968). The Ningbing Group forms outcrops in a narrow north-northwesterly trending belt from Eight Mile Creek, south of Pincombe Range, through Jeremiah Hills to Brolga Spring. Due to the presence of local disconformities and rapid lateral facies changes, the Ningbing Group varies greatly

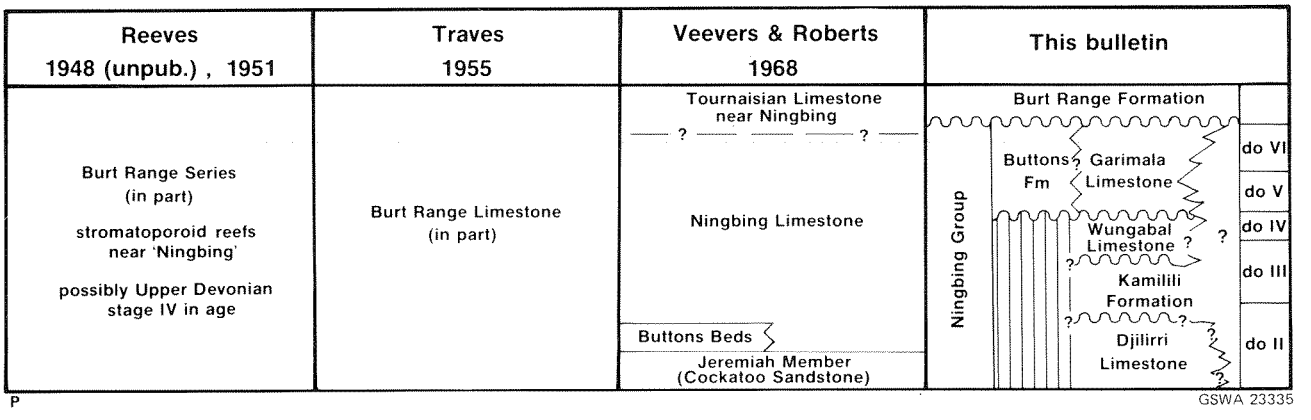

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Figure 76. Relationship of previous stratigraphic nomenclature for the Famennian of the Bonaparte Basin.

in thickness with a known range of 171 m, in Ningbing 1, to 1166 m in Keep River 1 in the Northern Territory. The five units which make up the Ningbing Group are the Djilirri Limestone, Kamilili Formation, Wungabal Limestone, Garimala Limestone, and Buttons Formation. These are distinguished as facies which may be separated by local disconformities in the reef complex (Figs 75 and 76). On the Carlton Shelf the Ningbing Group conformably overlies the Cockatoo Group and is disconformably overlain by the Carboniferous Langfield and Weaber Groups, whereas on most of the Burt Range Shelf the unit disconformably overlies the Cockatoo Group and is conformably overlain by the Langfield Group. At the northern end of the Burt Range Shelf, near Sorby Hills, the Ningbing Group disconformably overlies the Precambrian of the Pincombe Inlier, or the Cambrian Antrim Plateau Volcanics, and is itself disconformably overlain by the Weaber Group.

DJILIRRI LIMESTONE

Definition: The Djilirri Limestone (Beere and Mory, 1986) is the basal unit of the Ningbing Group and encompasses both platform and marginal-slope facies of the early Famennian reef complex exposed in Ningbing Range and Jeremiah Hills. The unit is named after Djilirri, a prominent limestone hill, 1 km southwest of Ningbing homestead. The "Jeremiah Member" (Veevers and Roberts, 1968, p. 39) is included in the Djilirri Limestone because of its lithological similarity to the section north of, and along strike from, the type section for the "Ningbing Limestone" of Veevers and Roberts (1968) near Siggins Spring. Although dolomite and sandstone beds occur within the Jeremiah Member, the presence of these lithologies is not regarded as sufficient grounds for excluding the unit from the Djilirri Limestone. The dolomite is of secondary origin and sandstone beds (albeit poorly exposed) are common north of Siggins Spring and in the eastern part of the Jeremiah Hills. The type section of the Djilirri Limestone is the south side of The Gorge from 15°10′40″S, 128°37′10″E (base) to 15°10′55″S, 128°37′55″E (top). As this section consists entirely of platform facies it is supplemented by a reference section, 2.5 km northwest of Tanmurra bore, which includes approximately 100 m of marginal-slope breccia, from 15°04′50″S, 128°48′55″E (base) to 15°04′30″S, 128°36′55″E (top).

Lithology: Within the back-reef subfacies, skeletal, oolitic, oncolitic and peloidal grainstone and packstone predominate although calcarenite and sandstone interbeds are locally common, especially in the exposures north of Siggins Spring. The alternation of terrigenous and carbonate beds in that area may represent a cyclic control of sedimentation, in contrast to the dominantly carbonate sections on the eastern side of Ningbing Range (Fig. 77). Adjacent to Ningbing homestead thickly bedded fenestral limestone, with rare stromatolite horizons, forms much of the craggy outcrop. Also near Ningbing homestead, large unnamed bivalves are common in the back-reef subfacies adjacent to the reef flat (*c.f.* Fig. 78).

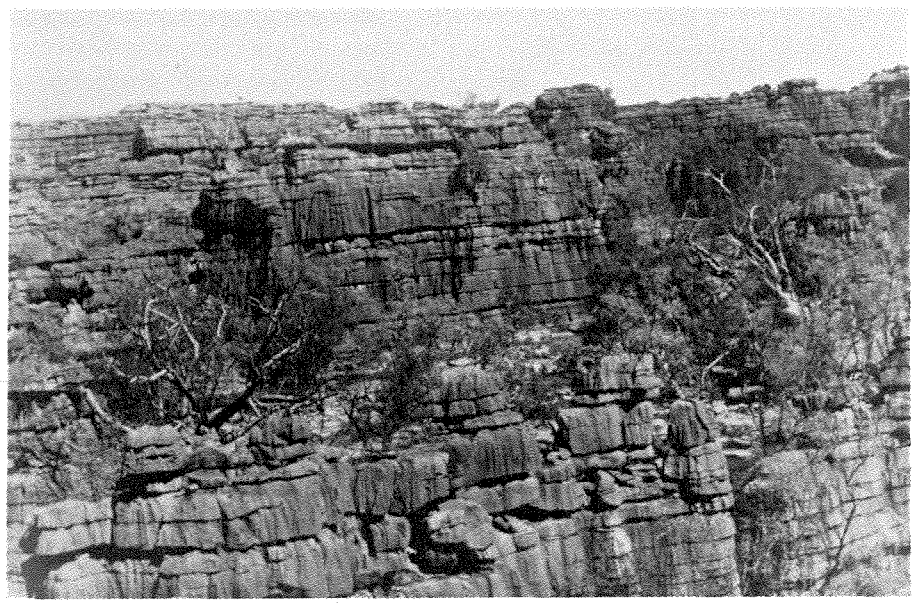

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Figure 77. Back-reef subfacies of the Djilirri Limestone northwest of Ningbing homestead. The regular continuous bedding is one of the most conspicuous features of this subfacies.

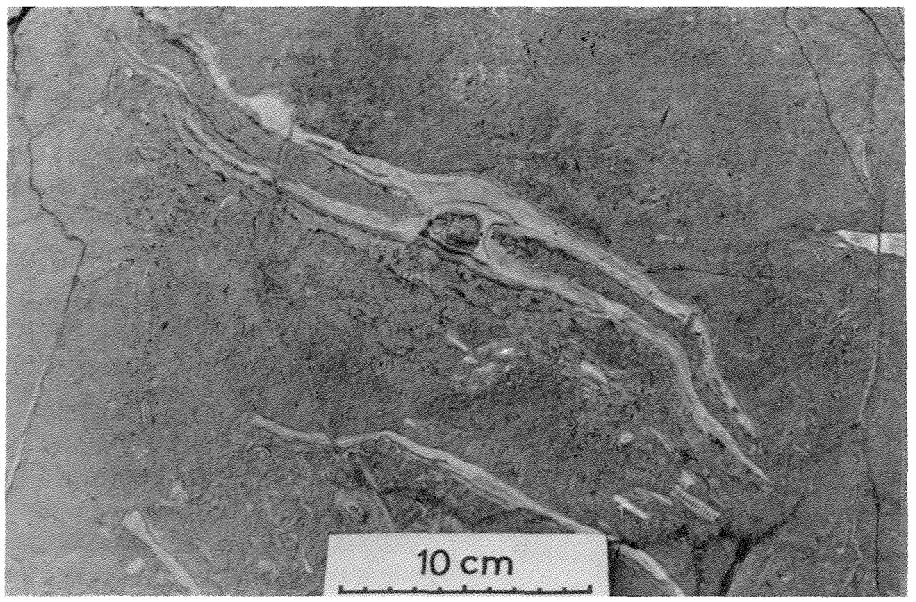

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Figure 78. Unnamed bivalve from back-reef subfacies. Djilirri Limestone near Brolga Spring at 14°54′50″S, 128°34′50″E

The reef-margin and reef-flat subfacies of the Djilirri Limestone consist of massive and crudely bedded microbial boundstone, respectively, in which *Sphaerocodium* and *Girvanella* are major constituents (Fig. 79). *Renalcis*, which is one of the important components in the Famennian reef-margin subfacies in the Canning Basin, is relatively rare in the Bonaparte Basin and generally comprises less than 0.5% of these rocks.

Both reefal-slope and fore-reef subfacies can be recognized in the marginal-slope facies of the Djilirri Limestone. The fore-reef subfacies consists predominantly of crudely bedded, limestone breccia. It has a silt-rich matrix, which is generally preferentially dolomitized leaving the clasts (especially those of reefal origin) in a matrix of sand-sized dolomite crystals. At the southern end of Ningbing Range the fore-reef of the Djilirri

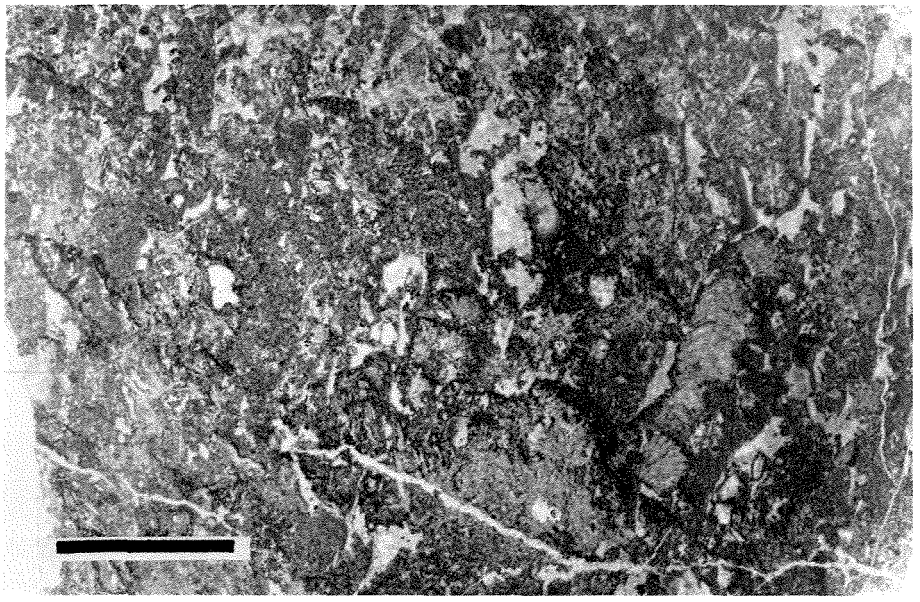

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Figure 79. Skeletal, microbial, algal boundstone from the reef-margin subfacies. Djilirri Limestone in The Gorge at 15°10′55″S, 128°37′50″E. Specimen 73405B. Bar scale is 1 cm.

Limestone consists predominantly of thinly bedded, skeletal, peloidal, lithoclast grainstone. The reefal-slope subfacies is known from only one locality 700 m west of Tanmurra bore, in a hill (40 m high) surrounded by the overlying Kamilili Formation and overlain, at the northern end, by back-reef carbonate also of the Djilirri Limestone. At this locality the reefal-slope consists of crudely bedded boundstone with large patches of skeletal packstone, dipping at 17° to the east.

Stratigraphic relationships: The Djilirri Limestone conformably overlies the Hargreaves Formation of the Fransnian Cockatoo Group. The contact is generally poorly exposed except in the Knob Peak area. In Ningbing Range the Djilirri Limestone is disconformably overlain by the Kamilili Formation or Garimala Limestone. Although there are, as yet, no subsurface data on the Djilirri Limestone it is likely that the marginal-slope facies passes into basinal facies east of the outcrop belt; *i.e.* basinwards the Djilirri Limestone possibly interfingers with the Kamilili Formation as shown in Figure 80.

Distribution and thickness: The Djilirri Limestone crops out in the Jeremiah Hills and along the western side of Ningbing Range although outcrop is discontinuous north of Surprise Creek. The type section in Ningbing Range consists of approximately 135 m of back-reef subfacies limestones, but also includes an outcrop of reef-margin subfacies (35 m high) at the eastern end of the section. The section through Siggins Spring at the southern end of Ningbing Range, chosen by Veevers and Roberts (1968) as the type for the "Ningbing Limestone", contains the greatest thickness of Djilirri Limestone back-reef subfacies in Ningbing Range (220 m). The thickest section of Djilirri Limestone is in the Jeremiah Hills where 400 m of back-reef limestones were measured by Veevers and Roberts (1968; sections 442 plus 447). In that area the basal 110 m was distinguished as the "Jeremiah Member" by these workers.

Fossils and age: The palaeontology of the Djilirri Limestone was summarized by Roberts and others (1967) under back-reef and reef of the "Ningbing Limestone".

In Ningbing Range the only evidence for the age of the unit is near Ningbing homestead where Druce (1969) recovered a single specimen of the conodont *Icriodus rectus* from the back-reef subfacies. This species ranges throughout the Frasnian into the middle Famennian (doI–III). From the Jeremiah Hills Druce (1969) recorded *Pelekysgnathus planus* (reported as *P. peejayi*) and *Apatognathus varians klapperi* from Veevers and Roberts' (1968) section 443. The two species overlap in their ranges within the lower *marginifera* zone (do II–III) and suggest a middle Famennian age. Based on these two conodont ages and the stratigraphic position of the Djilirri Limestone, an early to middle Famennian age is suggested for the unit.

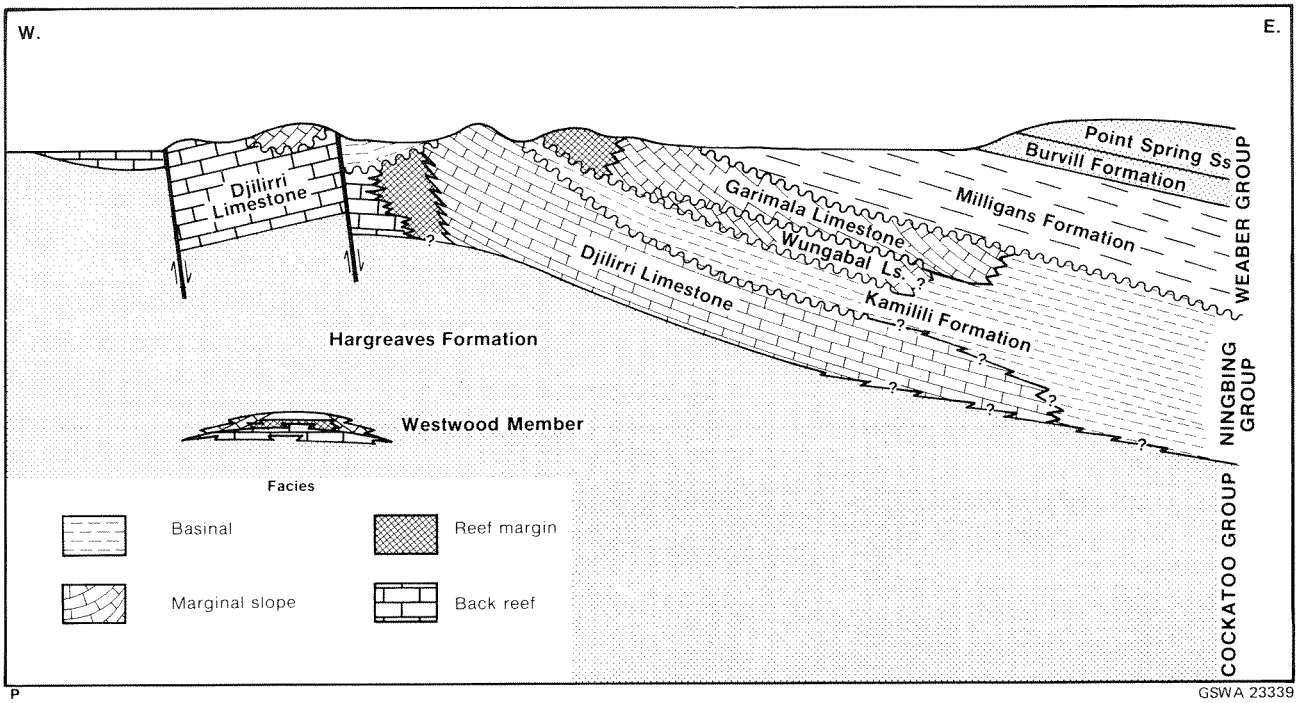


Figure 80. Diagrammatic section across Ningbing Range showing the relationships of units in the Ningbing Group.

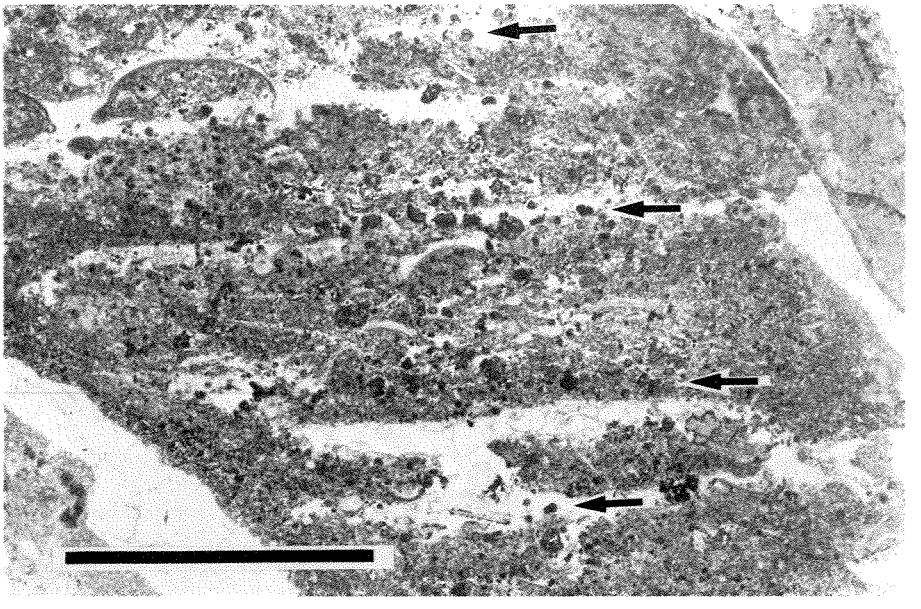
KAMILILI FORMATION

Definition: The Kamilili Formation (Beere and Mory, 1986) is named after Kamilili or Long Spring, 10 km northeast of Knob Peak on the edge of the tidal mudflats. The unit contains basinal and marginal-slope facies consisting of thinly bedded, fossiliferous, fine-grained packstone, shale, mudstone, and limestone breccia. Stromatolite boundstone of reef origin is also present in this unit, in Ningbing 1. In outcrop the Kamilili Formation disconformably overlies the Djilirri Limestone and is disconformably overlain by the Wungabal or Garimala Limestones. Subsurface data, however, suggest that the Kamilili Formation is at least partly equivalent to the Garimala Limestone and so implies equivalence with the intervening Wungabal Limestone. The Kamilili Formation is also implied to be laterally equivalent to the Djilirri Limestone in the subsurface. The type section is a low ridge, 2 km northwest of Tanmurra bore from 15°04′45″S, 128°37′05″E (base) to 15°04′55″S, 128°37′15″E (top), being the only non-faulted section exposed. The lower and upper contacts are disconformable with the Djilirri and Garimala Limestones, respectively.

Lithology: The Kamilili Formation contains thin- to medium-bedded terrigenous and carbonate lithologies. Terrigenous lithologies dominate, comprising fossiliferous mudstone and siltstone of the basin facies. In outcrop these fine-grained terrigenous sediments are only evident from the thinly bedded character of the limestones. Carbonate lithologies are of three main types: very fine-grained skeletal packstone and wackestone; limestone breccia; and stromatolitic boundstone. The first lithology allows for ready recognition of this formation in outcrop and forms a scree of limestone flags. Cross-bedding and ripple cross-lamination within the wackestone and packstone beds suggest deposition by weak currents. In thin section the foraminifer *Uralinella* comprises up to 10% of this lithology (Fig. 81). Limestone breccia forms beds up to 1.5 m thick in the Kamilili Formation and is interbedded with the thinly bedded lithologies at most levels in the unit. But it is most common in the more westerly outcrops in the Tanmurra area and the easterly outcrops near Knob Peak. Small blocks of reefal material are common, suggesting the breccias accumulated in a marginal-slope facies. Stromatolite biostromes are relatively minor in outcrop and consist of beds of massive microbial boundstone, generally less than 0.5 m thick, interbedded with the flaggy skeletal packstone.

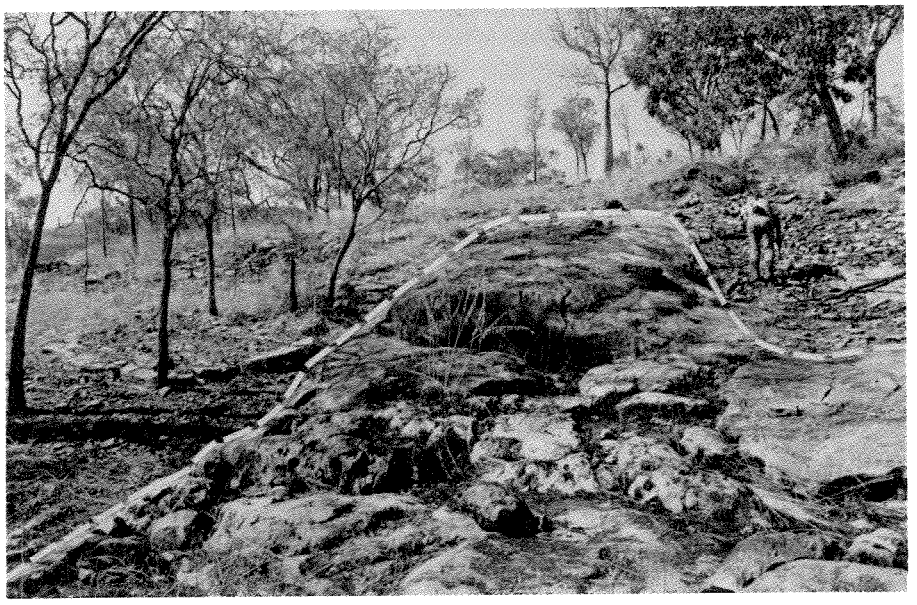
In Ningbing 1 this unit is composed of boundstone, with abundant submarine cement filling fractures and cavities in the boundstone, which suggests a stromatolite reef.

Stratigraphic relationships: In outcrop the Kamilili Formation disconformably overlies the Djilirri Limestone. The formation overlaps platform and marginal-slope facies of the older unit, preserving a flat erosion surface which has been planed smooth possibly by submarine erosion (Fig. 82).



GSWA 23340

Figure 81. Fine-grained skeletal wackestone from the Kamilili Formation near Knob Peak at 14°57′10″S, 128°34′45″E. The foraminifer *Uralinella* (arrowed) makes up nearly 10% of this lithology. Specimen 66627B. Bar scale is 1 cm.



GSWA 23341

Figure 82. Disconformable contact between flaggy limestone of the Kamilili Formation (above) infilling an erosional gully in marginal-slope facies breccia of the Djilirri Limestone (below). Note the truncation of the flaggy limestone against the massive breccia in the centre of the photograph. Tanmurra Creek at 15°03′45″S, 128°36′35″E.

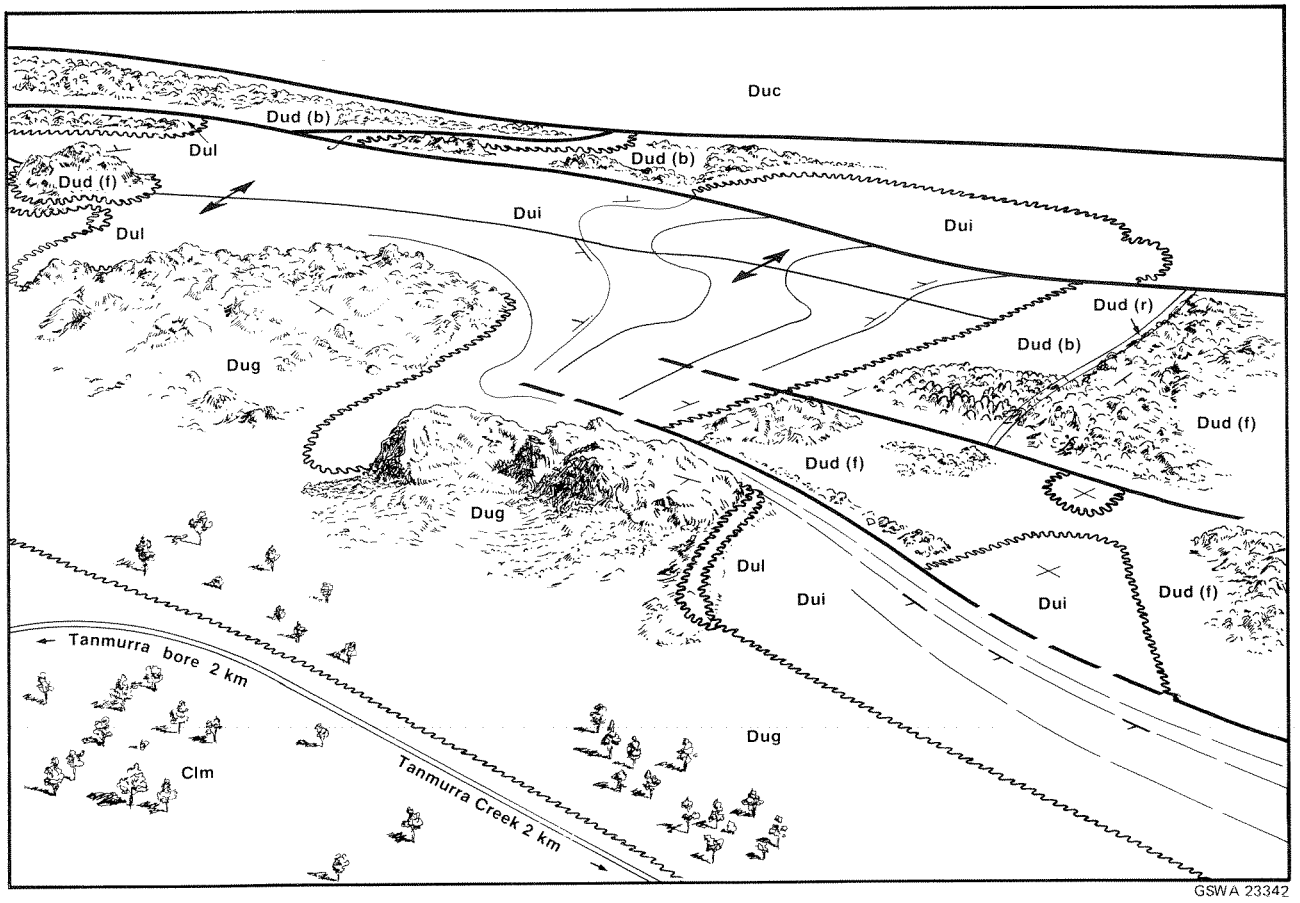


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Figure 83. View looking west across Ningbing Range 2.5 km northwest of Tanmurra bore, drawn from an oblique aerial photograph. Back-reef (b), reef-margin (r) and marginal-slope (f) facies of the Djilirri Limestone (*Dud*) are disconformably overlain by the Kamilili Formation (*Dui*), which is, in turn, disconformably overlain by the Wungabal (*Dul*) and Garimala (*Dug*) Limestones. The Ningbing Group is underlain by the Cockatoo Group (*Duc*) and overlain by the Milligans Formation (*Clm*).

The formation can also be seen onlapping against fault scarps of Djilirri Limestone (Fig. 83). Overlying the Kamilili Formation, with a local angular unconformable relationship, is the Wungabal Limestone which contains reworked blocks of Kamilili Formation limestone and shale. In places the Wungabal Limestone has been removed by another erosional event, and the Kamilili Formation is disconformably overlain by the Garimala Limestone. In Ningbing 1 the Kamilili Formation is unconformably overlain by the Carboniferous Milligans Formation, with a distinct divergence of dip directions evident on the dipmeter logs. The disconformities which bound this unit in outcrop do not appear to persist any great distance in the subsurface.

In the subsurface, thinly bedded shale and limestone (here identified as the Kamilili Formation) lie down dip from outcrop of the Garimala Limestone in Australian Aquitaine Minerals' drill holes WBN 5003 and 5001 (Plate 3, sections CC', GG'). Thus the Kamilili Formation may be inferred to also lie down dip from the intervening Wungabal Limestone (Fig. 80). Since it seems likely that the marginal-slope facies of the Djilirri Limestone passes into basinal facies east of the belt of outcrop, then the Kamilili Formation may also be equivalent to the Djilirri Limestone in the subsurface (Fig. 80).

Distribution and thickness: The Kamilili Formation forms outcrops in three main areas in Ningbing Range: just north of Surprise Creek; between Tanmurra bore and Tanmurra Creek; and near Knob Peak. Only in the Tanmurra area are relationships with surrounding units unequivocal. In the type section the formation is 160 m thick. This thickness is comparable to the 150 m intersected (without the base of the unit being reached) in Australian Aquitaine Minerals' drill hole WBN 5002 next to Tanmurra bore, and the 152 m in WBN 5003, north of Tanmurra Creek. Near Surprise Creek, Australian Aquitaine Minerals' drill hole WBN 5001 and BHP Minerals' drill hole NB-81-2 intersected 200 m and 253 m of Kamilili Formation, respectively, without reaching the base of the unit. A possible maximum thickness of 750 m for the Kamilili Formation may be inferred in this area (Fig. 84). Furthermore it may also be inferred that the Kamilili Formation continues several kilometres east of Ningbing Range in the subsurface, below the Carboniferous Milligans Formation (Figs 84 and 85).

Fossils and age: The Kamilili Formation contains large numbers of fossils particularly in the thinly bedded grainstone. Especially abundant are brachiopods, crinoids, corals and the foraminifer *Uralinella* sp. Also present are bryozoans, stromatolites, stromatoporoids, miospores, gastropods and conodonts, as well as rare ammonoids and trilobites. Of these groups only conodonts and miospores have received any attention. R. S. Nicoll (written comm. 1982) recovered conodonts of the *marginifera* zone (do II–III) *i.e.* early to middle Famennian, from surface samples near Tanmurra Creek. In nearby Australian Aquitaine Minerals' drill hole WBN 5003 he recovered

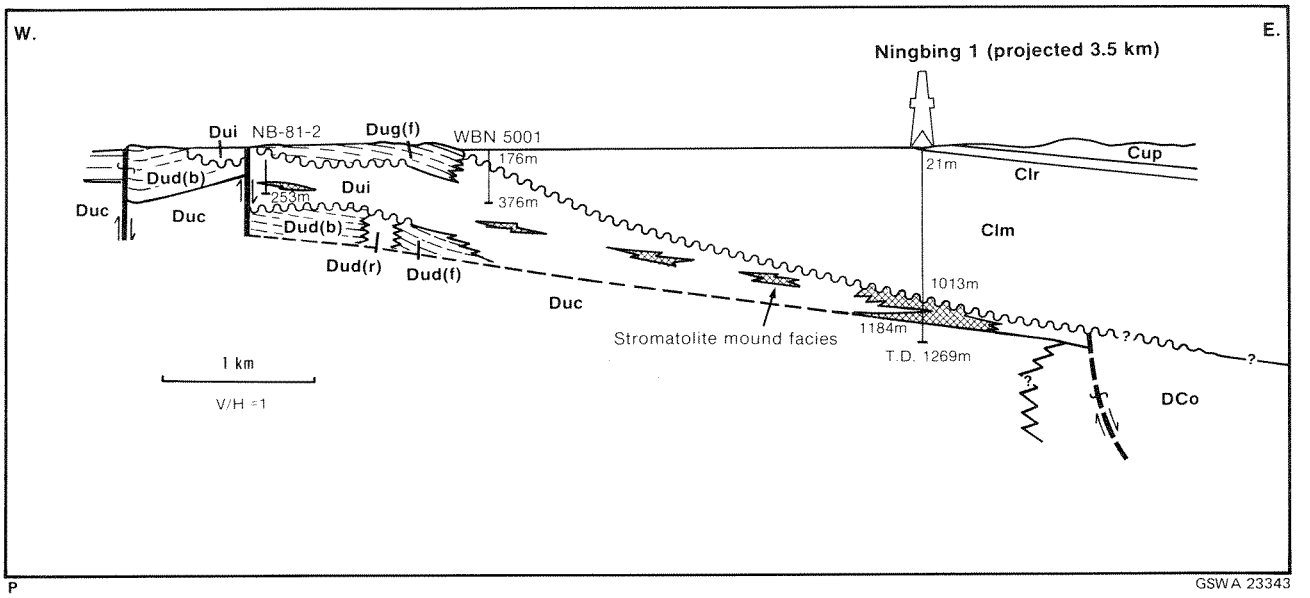


Figure 84. **East-west cross-section across the Ningbing Group, 2 km north of Surprise Creek, with Ningbing 1 projected 3.5 km from the south. *Cup* — Point Spring Sandstone, *Clr* — Burvill Formation, *Clm* — Milligans Formation, *DCo* — Bonaparte Formation, *Dug* — Garimala Limestone, *Dui* — Kamilili Formation, *Dud* — Djilirri Limestone, *Duc* — Cockatoo Group.**

Palmatolepis perlobata perlobata from the middle of the Kamilili Formation (255–260 m) which suggests the upper *triangularis* to *crepida* zones (do II), *i.e.* an early Famennian age. Higher in this hole the presence of *Apatognathus varians klapperi* indicates the *marginifera* to lower *styriacus* zones (do III–IV), *i.e.* a middle Famennian age. By comparison Truswell (1981) recovered spores of the *Retispora lepidophyta* assemblage from 190 m and 322 m in this hole, suggesting a latest Famennian age (do VI). However, Playford (*in* Lee, 1982) later identified these spores as *Retispora archaeolepidophyta* and suggested an early Famennian age. Based on its deduced lateral equivalence in the subsurface with all of the other units of the Ningbing Group, the Kamilili Formation is likely to have an early to late Famennian age. In Ningbing 1, Nicoll (*in* Garside, 1982) recovered a single specimen of *Palmatolepis glabra pectinata* from a core between 1022 m and 1023 m in limestone and shale, 9 m below the top of the Kamilili Formation. The species is restricted to the *crepida* to *marginifera* zones (do II-III) and, if not reworked, suggests that the mid to latest Famennian is missing in Ningbing 1.

WUNGABAL LIMESTONE

Definition: The Wungabal Limestone (Beere and Mory, 1986) is named after Wungabal (Attack Spring) 14 km east-northeast of Knob Peak on the edge of the tidal mudflats. The unit consists predominantly of bedded red mudstone with red skeletal wackestone and mudstone with microbial laminations deposited in a marginal-slope facies. The type section is west of Tanmurra bore from 15°05′40″S, 128°37′45″E (base) to 15°05′45″S, 128°37′35″E (top) being the thickest and best exposed section in the unit. Neither the upper nor the lower contacts are exposed in this westerly dipping section, as the top of this section is faulted against Kamilili Formation while the lower contact is obscured by the overlying easterly dipping Garimala Limestone (Plate 3, section EE′). The best exposure of the lower contact with the Kamilili Formation lies 1 km west-southwest of Tanmurra bore at 15°05′55″S, 128°36′50″E. The contact with the overlying Garimala Limestone is well exposed 400 m south of the type section (Fig. 86).

Lithology: The Wungabal Limestone consists predominantly of distinctive red intraclast mudstone with white sparry calcite cement. The clasts comprise red crinoidal boundstone with microbial laminations, quartz-silt wackestone, and peloidal packstone. The white sparry calcite cement is of marine origin and contains red calcareous-siltstone laminae (Fig. 87). *In situ* beds of lithologies similiar to those which make up the clasts in the breccias are common. The limestone breccias are similar to those of the Scheck Limestone of Jurassic age in Austria, described by Hudson and Coleman (1978), and are here referred to as "scheck" breccias.

Of all the units in the Ningbing Group the Wungabal Limestone contains the largest cyanobacterial component especially noticeble in neptunian dykes. A distinctive lithology, best developed in this unit, is dominated by large (up to 60 cm in diameter) spar balls found in neptunian

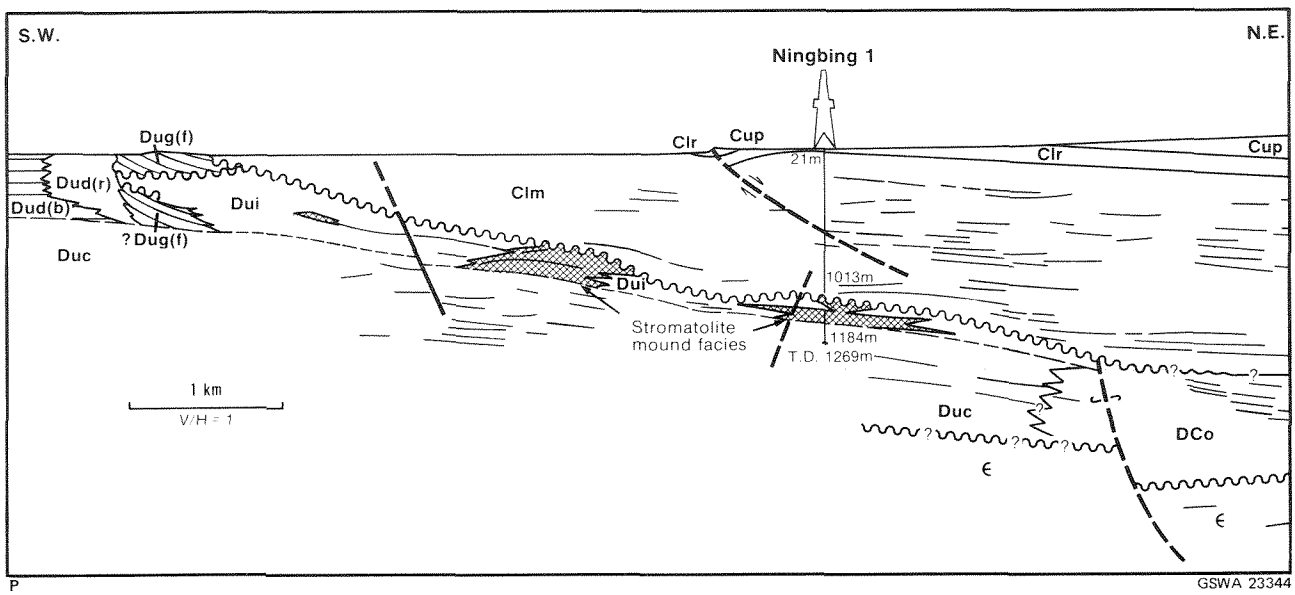
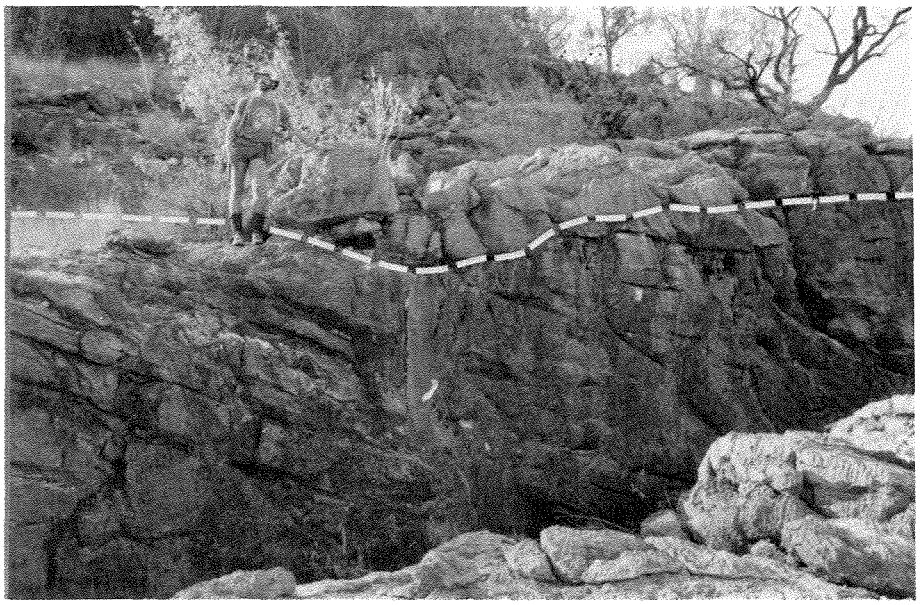


Figure 85. Geological cross-section along Australian Aquitaine Petroleum seismic line BWA-81-206. See Figure 84 for explanation of symbols and Plate 3 for location of seismic line.

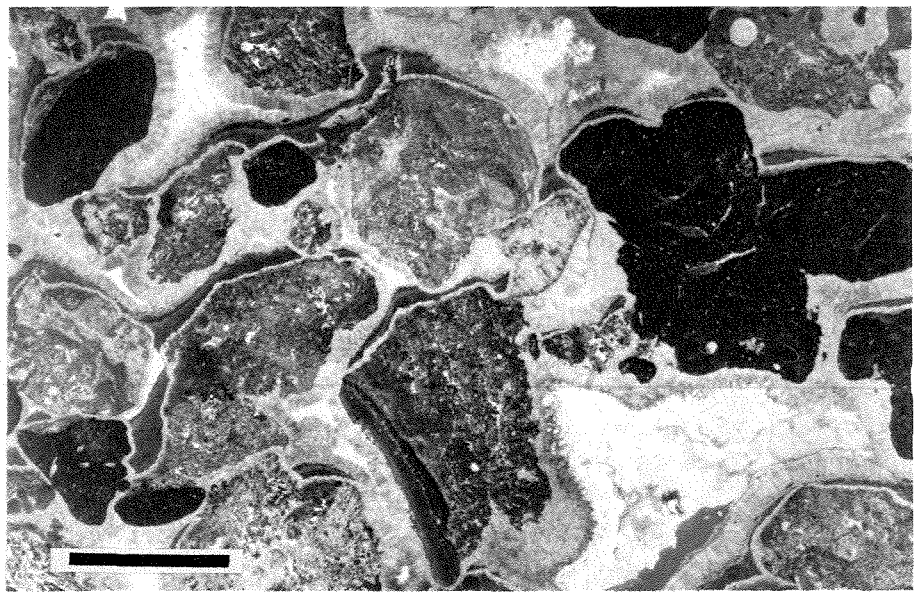


GSWA 23345

Figure 86. Angular unconformity (dashed line) between marginal-slope facies of the Wungabal Limestone (below) and that of the Garimala Limestone (above). An angular divergence of 14° between the two units is evident at this locality. 700 m southwest of Tanmurra bore at 15°06′00″S, 128°37′45″E.

dykes, similar to those described by Playford (1984) from the Canning Basin. The balls consist of alternating layers of fine-grained micritic spar, with some microbial laminations, coating angular fragments of the same composition in a matrix of calcareous mudstone of fine-grained dolomite (Fig. 88). These spar balls probably formed in the neptunian dykes in which they are found, and obtained their spherical shape by episodic movement due either to the opening up of the dykes or wave surges.

Stratigraphic relationships: An angular unconformity between the Wungabal Limestone and underlying Kamilili Formation is evident, 1 km west-southwest of Tanmurra bore. Here the lower contact of the Wungabal Limestone dips gently to the east and cuts across Kamilili Formation limestones which dip to the southwest. Elsewhere this contact is obscured by scree, but the presence of reworked blocks of Kamilili Formation near the base of the Wungabal Limestone suggests that the contact is disconformable.



GSWA 23346

Figure 87. Red "scheck" breccia, in which the clasts consist of red microbial boundstone, and peloidal packstone coated by white calcite cement. Wungabal Limestone next to Tanmurra bore at 15°05′40″S, 128°37′45″E. Bar scale is 1 cm.

Disconformably overlying the Wungabal Limestone is the Garimala Limestone. Only at two localities is an angular divergence evident between the two units. West of Tanmurra bore the Wungabal Limestone dips at 23° to the west, due to step faulting prior to the deposition of the Garimala Limestone which dips at 12° to the east (Plate 3, section EE'). The other locality at which an angular divergence between the two units is evident is 700 m southwest of Tanmurra bore (Fig. 86). East of Ningbing Range the Wungabal Limestone is inferred to pass into basin facies (Kamilili Formation) with the local angular unconformities above and below the Wungabal Limestone restricted to the vicinity of Ningbing Range (Fig. 80).

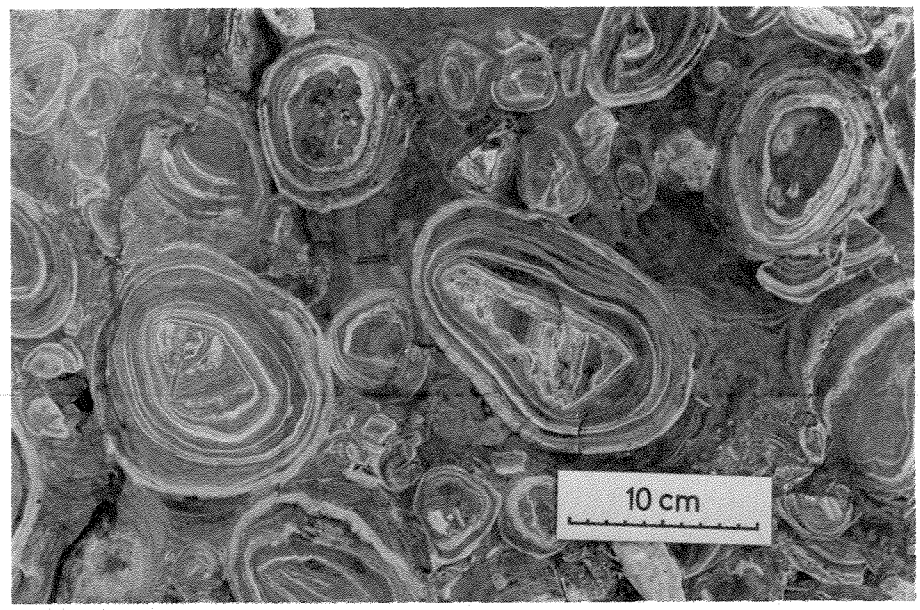
Distribution and thickness: Outcrop of the Wungabal Limestone is discontinuous and is largely restricted to a belt, 6 km long, on the eastern side of Ningbing Range, in the Tanmurra area, from 1 km south of Tanmurra bore to just north of Tanmurra Creek. Another outcrop tentatively assigned to the Wungabal Limestone lies 4 km northwest of Ningbing homestead, in contact with strongly dolomitized reef-margin subfacies of the underlying Djilirri Limestone. In the Tanmurra area the thickness of the Wungabal Limestone can be measured in only three sections: the type section where 100 m is exposed, although neither the upper nor lower contact can be observed; in a small section 400 m to the south of the type in which only 30 m is exposed, due to a lower faulted contact; and in Australian Aquitaine Minerals' drill hole WBN 5002 in which 35 m of Wungabal Limestone is present. Elsewhere the Wungabal Limestone either outcrops as scree, and is probably less than 10 m thick, or is absent between the Kamilili Formation and Garimala Limestone.

Fossils and age: The age of the Wungabal Limestone is deduced from stratigraphic relationships, as the conodont faunas recovered by Druce (1969, samples 455–3A, B) are similar to those from the underlying Kamilili Formation possibly as a result of reworking from that unit. Based on its stratigraphic position between the Kamilili Formation and Garimala Limestone the Wungabal Limestone is mid–Famennian (do IIIβ–IV, Fig. 74).

The most important fossils are stratiform stromatolites which have produced much of the red carbonate. Also present, although rarely well preserved, are crinoids and brachiopods as well as rare bony-fish plates.

GARIMALA LIMESTONE

Definition: The Garimala Limestone (Beere and Mory, 1986) is the uppermost unit of the Ningbing Group in Ningbing Range. The unit is named after Garimala, the spring on Surprise Creek in The Gorge; in Aboriginal mythology Garimala is also the Rainbow Serpent. The Garimala Limestone consists predominantly of limestone breccia which accumulated in a marginal-slope facies. The type



GSWA 23347

Figure 88. **Large spar balls in a neptunian dyke in the Wungabal Limestone. The balls are composed chiefly of layers of fine-grained micritic cement coating angular fragments of the same composition. Tanmurra bore at 15°13'05"S, 128°39'25"E.**

section is 2 km north of Surprise Creek from 15°09′40″S, 128°38′15″E (base) to 15°09′15″S, 128°38′55″E (top).

Lithology: The Garimala Limestone consists predominantly of talus deposits indicating fore-reef subfacies. At Knob Peak, the unit also includes microbial boundstone (reef-margin subfacies). The fore-reef subfacies is dominated by peloidal-lithoclast grainstone and limestone breccia, either with a silt-rich matrix or radiaxial-calcite cement filling the space between lithoclasts (Fig. 89). The matrix usually consists of skeletal peloidal mudstone, and wackestone is often preferentially dolomitized leaving the limestone clasts largely unaffected. Where dolomitizing fluids have invaded limestone breccias with radiaxial-calcite cements, it is the clasts which are dolomitized while the impervious calcite cement remains unaffected. Lithoclasts in the limestone breccias are mostly from platform facies and include peloidal grainstone of back-reef origin, as well as microbial boundstone from reef-margin subfacies. The mixed conodont faunas recovered by Druce (1969) suggest that many of the clasts in this unit were reworked from an older reef complex, as well as from contemporaneous platform facies.

Stratigraphic relationships: In outcrop the Garimala Limestone unconformably overlies the Djilirri Limestone, Kamilili Formation and Wungabal Limestone. In the subsurface a rapid facies change occurs down dip into basinal facies (*i.e.* Kamilili Formation). This suggests that the break between the Garimala Limestone and underlying units, evident in outcrop, is of local significance only. The Garimala Limestone is disconformably overlain by the Carboniferous Milligans Formation or, at Paddys bore, by the Utting Calcarenite. The contact with the Milligans Formation is seen only in mineral-exploration drill holes along the eastern edge of Ningbing Range and north of the Jeremiah Hills.

Distribution and thickness: The Garimala Limestone crops out in an almost continuous belt of easterly dipping, marginal-slope facies, along the eastern side of Ningbing Range from Knob Peak to 2 km north of Ningbing homestead. In addition, there are two isolated areas of westerly dipping, marginal-slope facies of this unit of the western side of Ningbing Range, 1.5 km southwest of Tanmurra bore and just south of Tanmurra Creek. The Garimala Limestone varies in thickness from 150 m in the type section to 340 m near Paddys bore in Australian Aquitaine Minerals' drill hole WBN 5005 (Plate 3, section BB′). These thicknesses may not represent the true structural thicknesses, as the dips in this unit of marginal-slope facies are largely depositional.

Fossils and age: Of the diverse fossils present in the Garimala Limestone very few have been identified. These include the brachiopod *Cyrtospirifer ningbingensis* (Roberts, 1971), the alga *Sphaerocodium* and a number of conodonts recorded by Druce (1969). The conodont faunas recovered by Druce are mixed, as they include species reworked from the early and mid

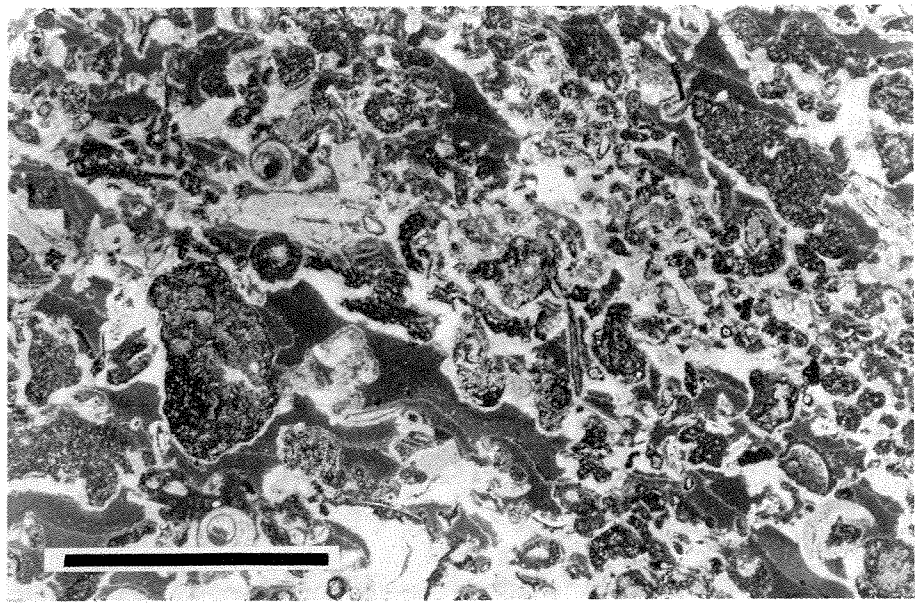


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Figure 89. Peloidal lithoclast grainstone with geopetal calcareous-mud infill in marginal-slope facies. Garimala Limestone north of Surprise Creek at 15°13′05″S, 128°39′25″E. Specimen 66618. Bar scale is 1 cm.

Famennian. The resricted ranges of some species, in particular *Palmatolepis gracilis sigmoidalis, Polygnathus znepolensis, P. hassi, Bispathodus aculeatus* and *Spathognathodus ziegleri* indicate that this unit was deposited in the *styriacus* and *costatus* Zones (do V–VI), *i.e.* in the late Famennian.

BUTTONS FORMATION

Definition: The Buttons Formation ("Buttons Beds" of Veevers and Roberts, 1968) is a sequence of sandy and skeletal limestone, lying between the Frasnian Cockatoo Group and the Carboniferous Burt Range Formation in the Burt Range Shelf. The unit is named after Buttons Crossing on the Ord River and its type section, as defined by Veevers and Roberts (1968, p. 59), is 2 km downstream on the east bank from 15°37′50″S, 128°42′00″E (base) to 15°36′50″S, 128°41′10″E (top).

Lithology: In the type section the Buttons Formation consists of thin-bedded, alternating, skeletal wackestone and grainstone, with sandy and silty micrite. The skeletal carbonate commonly forms discontinuous stringers with vertical, calcite-filled veins which do not continue into the surrounding sandy micrite. These veins suggest that the discontinuous mature of the bedding results from disruption during differential compaction. Elsewhere, outcrop of the Buttons Formation (Eight Mile Creek and Sorby Hills areas) is poor or has a substantially greater clastic content. In these areas the Buttons Formation contains thick beds of cross-bedded sandstone with sandy and laminated carbonate beds which are much more strongly dolomitized than in the type section.

Stratigraphic relationships: Although the lower contact is nowhere exposed, the Buttons Formation overlies the Cockatoo Group presumably with a disconformity, since the early to mid Famennian sequence is missing from the Burt Range Shelf. In the belt of outcrop 24 km east of the type section, the Buttons Formation is conformably overlain by the Carboniferous Burt Range Formation. The overlying unit is not exposed near the type section. The Buttons Formation is coeval with the Garimala Limestone.

Distribution and thickness: Apart from the type section the only other outcrops of Buttons Formation are in a strike belt, 20 km long, east of Eight Mile Creek, and at Sorby Hills. The unit is 350 m thick in the type section compared to 300 m at the northern end of the outcrop belt at Eight Mile Creek.

Fossils and age: While the Buttons Formation contains a diverse number of fossil groups, summarized in Roberts and others (1967), most of the identified fossils in this unit are from the type section. To date only three groups, ostracods (Jones, 1968, 1985), conodonts (Druce, 1969) and miospores (Playford, G., 1982), have been utilized in determining the age of the formation. Playford suggested a latest Famennian (do VI) age based on microfloras from the type section and considered that the early Famennian age proposed by Druce (1969) is from reworked conodont specimens. Jones (1985) subsequently proposed a latest Famennian (do V–VI) age for the Buttons Formation, based on the treposellid ostracods described in his 1969 paper.

UNDIFFERENTIATED NINGBING GROUP

Three kilometres northwest of Limestone Mill, an isolated sequence of thin- to medium-bedded skeletal packstone, 300 m thick, is exposed. On lithological criteria the sequence is difficult to distinguish from the back-reef subfacies of the Djilirri Limestone to the south in Jeremiah Hills. However, conodonts from the upper (eastern) part of the Limestone Mill section suggest a late Famennian (do V–VI) age (R. S. Nicoll, written comm. 1982). Similarly, stromatoporoids indicate a Strunian (do IV–VI) age for the uppermost part of this section (A. E. Cockbain, pers. comm. 1982). By comparison Druce's (1969) faunas from the Djilirri Limestone to the south, in Jeremiah Hills, indicate an age not younger than middle Famennian (do III). It cannot be established without a detailed palaeontological investigation whether or not there was continuous deposition of back-reef subfacies throughout the Famennian in the Jeremiah Hills area. On the present evidence the Limestone Mill sequence is coeval with the Garimala Limestone and Buttons Formation, and it is assumed that there is also a time break between the Limestone Mill sequence and the Djilirri Limestone to the south. Due to the uncertain stratigraphic position of the Limestone Mill outcrop, this and the other isolated limestone outcrops north and east of Jeremiah Hills are referred to undifferentiated Ningbing Group (see Plate 1).

DOLOMITIZATION

Disscussion of dolomitization in the Famennian Ningbing Group is here largely concerned with field relationships in Ningbing Range. In that area the main trends of dolomitization are much more readily recognized than in the isolated outcrops in the Jeremiah Hills and the area of Sorby Hills–Eight Mile Creek.

Particularly noticeable in outcrop are zones of intense dolomitization: the distribution of these in Ningbing Range is shown in Figure 90. These zones are dominated either by fine-grained ferroan dolomite, which generally preserves most of the primary textures in the limestone it replaces, or by coarse non-ferroan dolomite which obliterates most primary textures, thereby making it difficult to recognize facies in the reef complex. Most of the intense dolomitization north of Tanmurra bore in Ningbing Range and in the Jeremiah Hills is of the former type. Dolomitization is of the latter type south of Tanmurra bore, at Sorby Hills, and in the mineral-exploration drill holes east of Ningbing Range. Three main trends in the areal distribution of dolomite are evident. Firstly, the most intense dolomitization is close to the major fault along the western side of Ningbing Range. Secondly, in the subsurface east of Ningbing Range the uppermost 50 to 120 m of the Ningbing Group (below the Milligans Formation) are strongly dolomitized and leached. By comparison, dolomitization along the eastern side of Ningbing Range, in a similar stratigraphic position, is comparatively minor. Thirdly, thinly bedded units with a high proportion of fine-grained terrigenous sediment (particularly the Kamilili Formation) are relatively unaffected by dolomitization in contrast with thicker bedded carbonate-dominated units and, in particular, carbonate units with sandstone interbeds (for example parts of the back-reef subfacies of the Djilirri Limestone). Impervious units are less likely to become dolomitized than permeable units, suggesting that fluid movement is important in determining whether a unit becomes dolomitized.

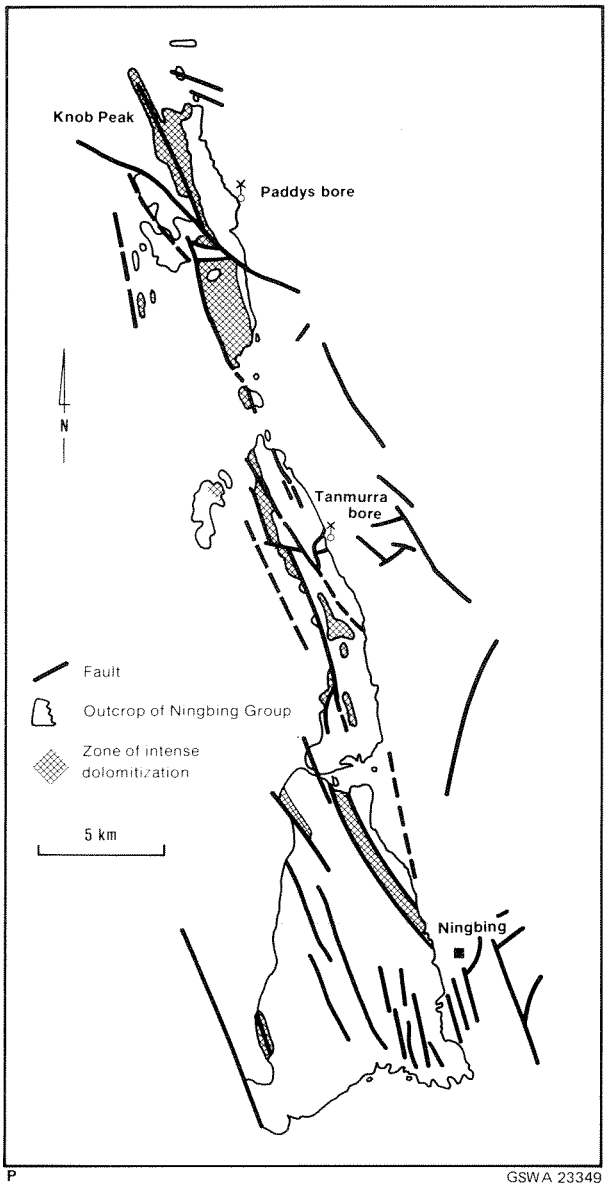

Figure 90. Distribution of areas of most intense dolomitization in the Ningbing Group, along Ningbing Range.

Along the western side of Ningbing Range, especially near Knob Peak and the Tanmurra area, the Djilirri Limestone is almost entirely replaced by fine-grained ferroan dolomite. Drilling in the Knob peak area by Australian Aquitaine Minerals revealed that the zone of ferroan dolomite is approximately 30 m thick; below this zone the Djilirri Limestone is almost unaffected by dolomitization. The concentration of such dolomitization, along the western margin of Ningbing Range, north of Siggins Spring and in the basal part of the Jeremiah Hills sequence, is probably the result of migration of dolomitizing fluids through the fault zones in those areas. The near-surface distribution of the ferroan dolomite in the Knob Peak area suggests that, at least in that area, such dolomite is teleogenetic (Choquette and Pray, 1970) in origin, forming as a result of tectonic uplift and exposure to the vadose and possibly phreatic zones.

Replacement of the uppermost part of the Ningbing Group (chiefly the Garimala Limestone) by coarse non-ferroan dolomite is associated with saddle dolomite in the subsurface east of Ningbing Range. The stratigraphic position of this zone of dolomitization suggests that the dolomitization may have occurred prior to the deposition of the Milligans Formation, in the vadose/phreatic zone during the late Tournaisian erosion of the Ningbing Group. However, a mesogenetic origin for this subsurface zone of dolomitization in the Ningbing Group is suggested by the presence of saddle dolomite (Radke and Mathis, 1980) and the relatively undolomitized condition of the outcrop at the eastern edge of Ningbing Range close to the overlying Milligans Formation. Dolomitizing fluids migrated up dip from the basin after the deposition of the Milligans Formation, with the

major effect of these fluids dissipating before reaching the level of the present outcrop belt.

From Ningbing homestead to The Gorge a north-northwest-trending belt of intensely dolomitized carbonate lies between back-reef subfacies to the west (Djilirri Limestone) and marginal-slope facies to the east (Garimala Limestone). This belt consists of low piedmont outcrops of massive coarse non-ferroan dolomite, with little of the original sedimentary fabric recognizable. At The Gorge the presence of undolomitized reef-margin subfacies of the Djilirri Limestone suggests that the dolomitized belt, lying along strike to the south-southeast, chiefly comprises this subfacies of the Djilirri Limestone. Similarly, small patches of relatively undolomitized, massive, microbial boundstone along the western edge of this belt confirm that at least the western side of this belt was once reef-margin subfacies. The width of the dolomitized belt (up to 1 km) suggests that adjacent facies may also be incorporated in this belt, although the adjoining reef-flat subfacies to the west is significantly less affected by dolomitization. Such dolomitization of the reef margin is in contrast with the platform margins of reef complexes in the Canning Basin, where porosity is believed to have been quickly destroyed by submarine cementation *in situ* (Playford, 1980). Consequently, the presence of this belt of dolomite in Ningbing Range is thought to be due to fluid migration along either a north-northwest-trending fault, now obscured by the coarse dolomite textures, or along the disconformity between the Djilirri and Garimala Limestones.

DEPOSITIONAL HISTORY

In the Famennian Ningbing Group a cycle of retreat then advance, of the reef complex, is evident from the vertical distribution of facies in Ningbing Range (Fig. 91). This cycle is in contrast with the entirely progradational sequence of the Famennian reef complexes in the Canning Basin (Playford, 1980; Fig. 14). This difference suggests that local tectonism had a significant control on the relative sea level, at least for the early Famennian in the Bonaparte Basin.

In the early Famennian a reef complex (Djilirri Limestone) was established along the edge of what is now Ningbing Range and the Jeremiah Hills (Fig. 92A). Whether the reef complex developed along the edges of fault blocks, as was the case in the Canning Basin (Playford, 1980), is difficult to assess. Such faults, if they exist in the Bonaparte Basin, have been obscured by the growth of the reef complex. At the southern end of Ningbing Range and at Surprise Creek, right-angle bends in the trend of the platform margin (Fig. 92A) are coincident with east-northeast photolineaments. These bends may be controlled by pre-Late Devonian basement topography since there is no evidence of Frasnian or Famennian faulting along the lineaments.

In the Tanmurra area there is some difficulty in reconstructing the early Famennian trend of the platform margin, due to the repetition of the east-northeast-trending belts of reef-margin subfacies

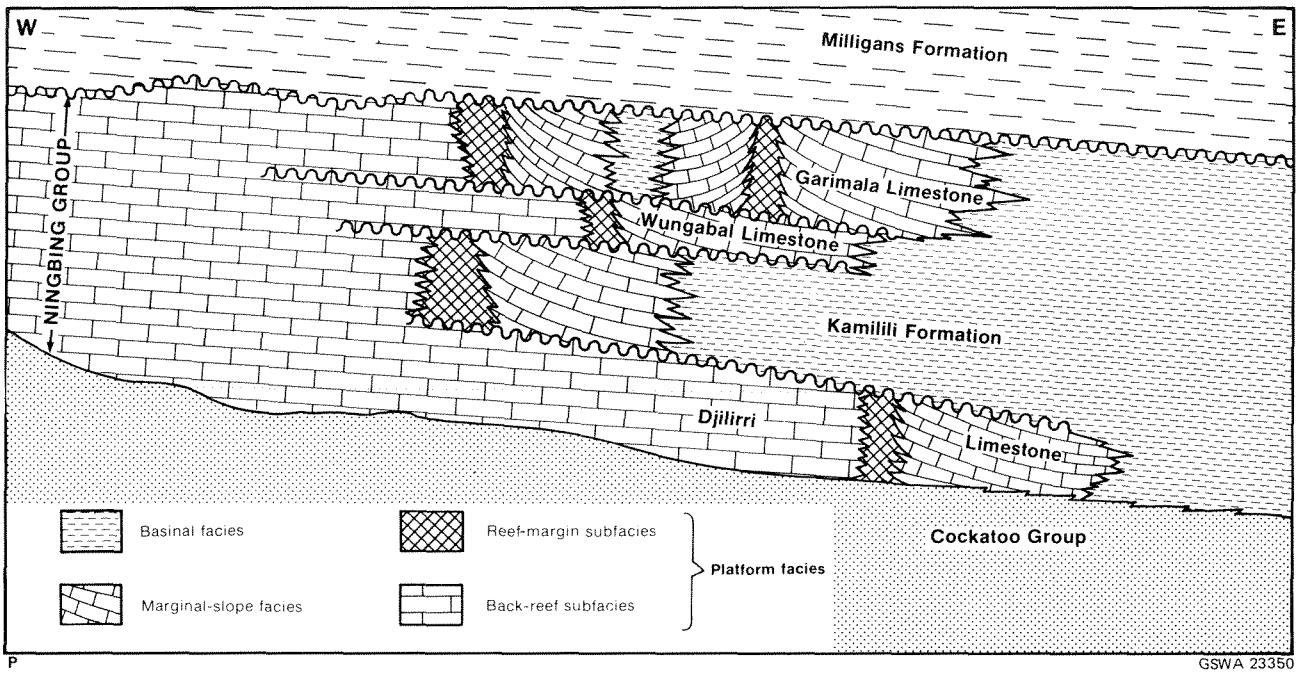

Figure 91. Schematic section across Ningbing Range illustrating the relationship of stratigraphic units and facies in the Famennian reef complex.

in that area (Plate 3). The cause of this repetition is obscure, as no faults were observed to separate the two belts.

Following the deposition of the early Famennian reef complex, a break in sedimentation was initiated probably by vertical movements along the north-northwest-trending fault system, which cuts Ningbing Range and has tilted the early Famennian back-reef subfacies. The break appears to be localized and does not extend a great distance into the basin (Fig. 91). A number of fault scarps are preserved as part of this erosion surface, over which basin and marginal-slope facies (Kamilili Formation) accumulated (Fig. 83). The sense of movement in this fault system is mainly down to the east, *i.e.* down-into-the-basin. This sense of movement is difficult to reconcile with the break in sedimentation along Ningbing Range, unless the break is a result of submarine erosion rather than subaerial exposure. The smooth nature of the erosion surface and its drowning by sediment, of basinal aspect, support the possibility of submarine erosion.

The encroachment of basin and marginal-slope facies (Kamilili Formation) over the early Famennian reef complex (Djilirri Limestone) can only be demonstrated north of Surprise Creek in Ningbing Range. Further south, deposition of the reef complex continued uninterrupted until the middle Famennian, as seen by the sequence of back-reef subfacies limestones in Jeremiah Hills (Fig. 74). This suggests that the two areas (Ningbing Range and Jeremiah Hills) were subjected to different tectonic controls, or that the fault system which resulted in the break in sedimentation in the early Famennian, in Ningbing

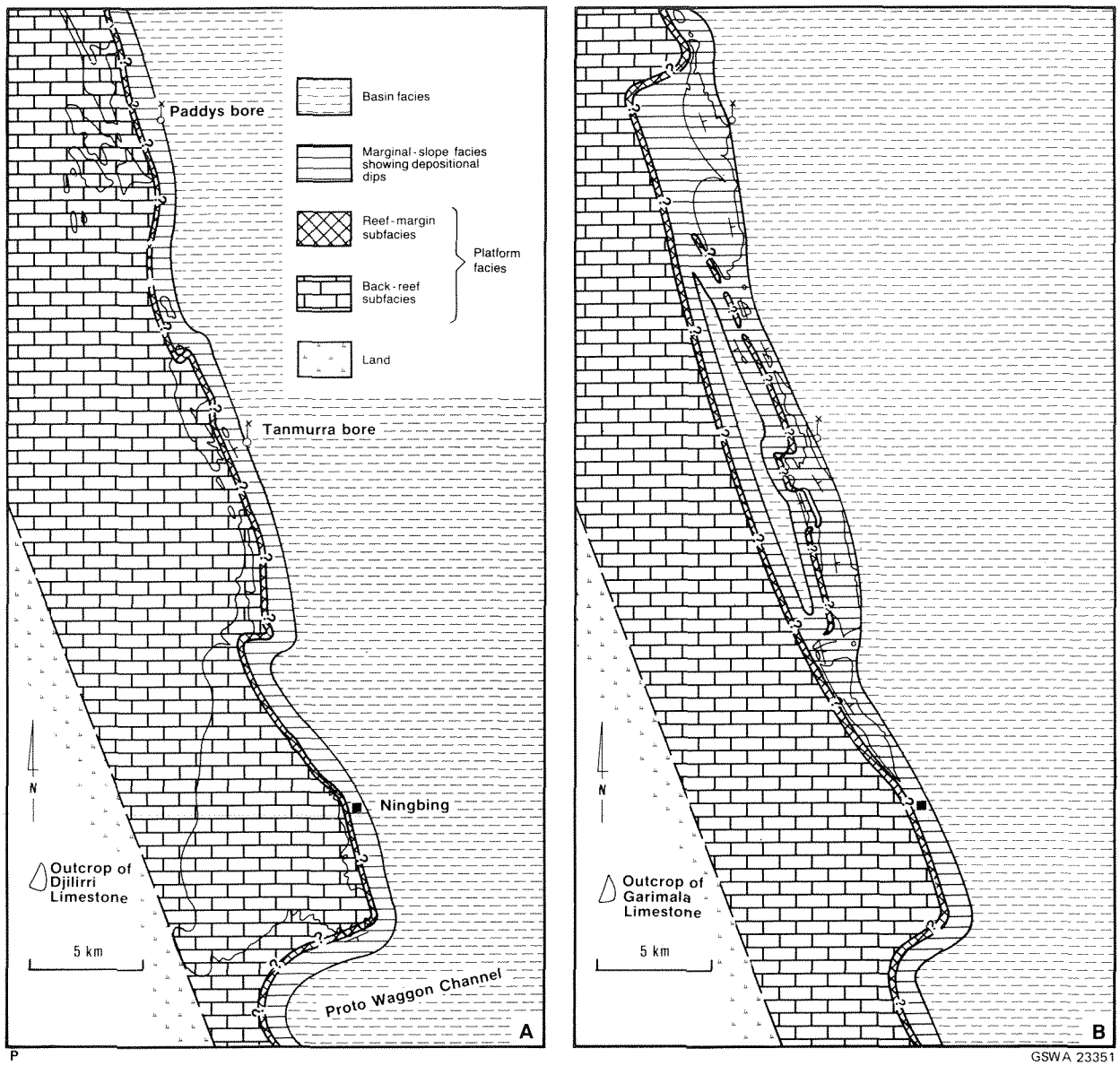

Figure 92. Palaeogeographic reconstruction of the reef complex along Ningbing Range in the early Famennian (A) and late Famennian (B).

Range, was not activated until the midde Famennian in the Jeremiah Hills. Following the backstepping of the platform margin in the late early Famennian, progradation of the reef complex recommenced in the middle Famennian with the deposition of red "scheck" breccias (Wungabal Limestone) of marginal-slope origin in the Tanmurra area. At the end of the middle Famennian, step faults tilted the sequence locally and thus created a local disconformity, with the deposition of the late Famennian reef complex over the tilted fault blocks (Plate 3, section EE').

In the late Famennian a belt of reef-margin subfacies was re-established along Ningbing Range with (in the Tanmurra area) marginal-slope facies to both the east and west. The presence of westerly dipping, marginal-slope facies, on the west side of the present outcrop belt, suggests that the Ningbing Range was a topographically high area in the late Famennian. This was possibly as a result of the fault movement at the end of the middle Famennian, and suggests the presence of another platform margin further to the west. It is conjectural whether or not the two belts of reef-margin were separated by basin facies, as shown in Figure 92B.

In Ningbing 1, the apparent lack of middle and late Famennian units is difficult to explain as being due entirely to either erosion or non-deposition, since nearly 500 m of middle to late Famennian sediments are preserved near the basin margin (in Ningbing Range). Possibly the Ningbing 1 area was a starved basin, in the middle and late Famennian, with a relatively thin sequence of basinal sediment deposited away from the basin margin. Such a sequence would be predominantly shaly and would be more easily eroded than the calcareous facies, near the basin margin, during the late Tournaisian regression.

CHAPTER 5

Tournaisian of the Bonaparte Basin

INTRODUCTION

The Tournaisian sequence of the Bonaparte Basin consists of the Langfield Group (Beere and Mory, 1986) and the coeval Bonaparte Formation (Veevers and Roberts, 1968). The former unit is restricted to the Burt Range Shelf and to small erosional pockets in the subsurface, of the Carlton Shelf, whereas the later unit occurs only in the subsurface of the Petrel Sub-basin. The Bonaparte Formation also extends into the Late Devonian but is poorly dated at that level.

LANGFIELD GROUP

The Langfield Group (Beere and Mory, 1986) consists of, in ascending order, the Burt Range Formation, Enga Sandstone, Septimus Limestone, and Zimmerman Sandstone. Guillaume (1966) referred to the group as the "Eight Mile Creek Group", however, the name had been previously used in New South Wales. Laws (1981) used the name "Keep River Group" for this sequence. "Keep River Formation" has been used by Guillaume (1966, p. 193) presumably as a synonym for the Keep Inlet Formation. Langfield Group is preferred to avoid confusion with this Permian unit. The name is derived from Langfield Point in the main area of outcrop in Burt Range (Plate 1, Fig. 93). All formations outcrop on the Burt Range Shelf; some have been recognized in oil-exploration wells. On the Carlton Shelf, only the Burt Range Formation is present, and the group has not been intersected in oil-exploration wells there.

The group overlies the Ningbing Group conformably, on the Burt Range Shelf, and disconformably on the Carlton Shelf (Plate 3, section HH'). Weaber Group sediments unconformably overlie the Langfield Group (Plate 1). The Keep Inlet Formation overlies the Langfield Group with angular unconformity. The group has a maximum thickness of about 900 m in the area of northern Enga Ridge–Mount Septimus (Fig. 94), and is of Tournaisian age (Veevers and Roberts, 1968).

BURT RANGE FORMATION

Definition: The Burt Range Formation ("Burt Range Series" of Matheson and Teichert, 1948, "Burt Range Limestone" of Noakes and others, 1952, amended by Veevers and Roberts, 1968) is a unit of limestone, sandy limestone, and minor sandstone, outcropping east of Eight Mile Creek and in Burt Range. The type section, designated by Veevers and Roberts (1968), is 8 km west-southwest of Milligans Hills (base 15°38′40″S, 128°55′00″E; top 15°39′20″S, 128°56′10″E), and consists of the lower and middle parts of the formation. Reference sections 9 km to the southwest and 20 km to the south-southwest were chosen by Veevers and Roberts to show the middle and upper parts of the unit. Section 2003 (Fig. 95) was measured 1 km south of the type section; sections 2005–2007 and 2016 were measured very close to the reference sections.

In the Sorby Hills area the formation has been divided into three members, the Sorby Dolomite Member, the Knox Siltstone Member, and the Gooseneck Member (in ascending order). The type section of the Sorby Dolomite Member is the interval 86.3–183.2 m in Elf Aquitaine Minerals Australia diamond drill hole WBS 5064 at 15°26′09″S, 128°58′22″E. Both the Knox Siltstone and Gooseneck Members are defined in diamond drill hole WBS 5048 at 15°27′07″S, 128°59′15″E, over the intervals 77.0–199.0 m and 199.0–280.4 m, respectively (Rowley and Lee, 1986).

Lithology: In outcrop the Burt Range Formation consists of four lithological units.

a) The lowest unit at 0–260 m consists of limestone, with rare sandy limestone and calcareous sandstone. Limestone consists of packstone and grainstone with minor mudstone, wackestone and boundstone. Major grain types are peloids, brachiopods, and crinoids, with lesser intraclasts, gastropods, oncolites, corals, and bryozoans. Laminar (fenestral) algae, nautiloids, and echinoids are rare. Veevers and Roberts (1968) recorded columnar stromatolites at 45 m above the base of this unit.

In the remainder of the section, between 260 m and 460 m, the amount of limestone and carbonate grain diversity decreases upwards; also sandstone content and bioturbation increase upwards.

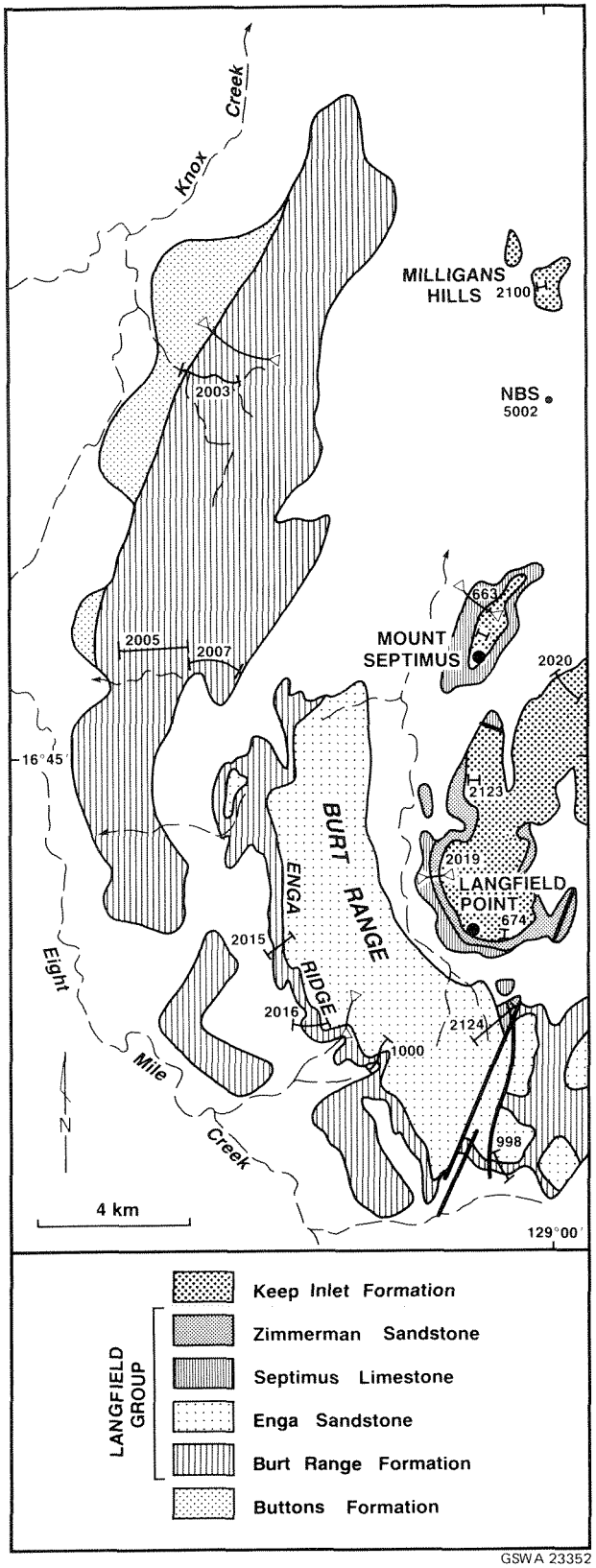

Figure 93. Location of measured sections of Langfield Group and Keep Inlet Formation on the Burt Range Shelf.

b) Between 260 m and 320 m the unit consists of limestone, sandy limestone, and minor calcareous sandstone. Limestone varies from wackestone to grainstone. Grains consist mainly of peloids, brachiopods and crinoids, with minor gastropods and rare bryozoans.

c) Between 320 m and 395 m the unit consists of limestone, sandy limestone, and calcareous sandstone. Limestone is mainly packstone, and major grain types are brachiopods and crinoids. *Skolithos* bioturbation is minor.

d) The section between 395 m and 460 m consists mainly of quartz sandstone and calcareous sandstone, with minor limestone and sandy limestone. Limestone varies from mudstone to packstone, and major grain types are brachiopods and crinoids; *Skolithos* bioturbation is abundant.

The lithological division is similar to that noted by Veevers and Roberts (1968) except that the measured thicknesses vary slightly and they included units 3 and 4 in one unit.

Away from the type area, outcrops at Spirit Hill and Sorby Hills are strongly dolomitized. Sorby Hills is a faulted anticline with Proterozoic rocks exposed in the core. The fault trends north-south, subparallel to the anticline axis. The Burt Range Formation crops out on the western downthrown limb. It consists of massive, and thin to medium (0.1–0.3 m thick) parallel-bedded dolomite, with minor thin interbeds of shaly dolomite. Irregular lamination and some *Skolithos* burrows are present. Undolomitized upper parts of the exposed section consist of fine- and coarse-grained grainstone, dominated by crinoid and brachiopod fragments, with minor stick and fenestral bryozoans, bivalves, and rare gastropods. The limestone texture and faunal composition indicate that these rocks are equivalent to the sequence at 260–320 m in the composite section. Rowley and Lee (1986) assign this outcrop to the Knox Siltstone Member.

In the subsurface in the vicinity of Sorby Hills, extensive drilling has been carried out by Elf Aquitaine Minerals Australia in order to delineate silver-lead-zinc mineralization. From this work Rowley and Lee (1986) recognized three members of the Burt Range Formation. The basal Sorby Dolomite Member consists of a sequence of recrystallized vughy dolomite, dolomitic siltstone and silty shale, typically bedded in cycles (3–5 m thick). Pseudomorphs after evaporites and poorly preserved microbial laminations have been recognized. The Knox Siltstone Member contains a thin basal argillaceous dolomite breccia, com-

prising reworked and slumped lithologies from within the member and from the underlying Sorby Dolomite Member. Above the basal dolomite breccia the unit consists of argillaceous dolomitic siltstone interbedded with bioclastic dolomite. The Gooseneck Member contains bioclastic limestone, sandy dolomite and argillaceous siltstone. The sequence is fossiliferous, well bedded, and contains nodular bedding.

At Spirit Hill, the Burt Range Formation is sandy, consisting of medium- to fine-grained calcareous and dolomitic sandstone, with minor quartz sandstone and sandy limestone (Veevers and Roberts, 1968). Fossils are sparse and consist mainly of crinoid columnals. The Burt Range Formation in Spirit Hill 1 (between 252 m and 610 m) is less sandy than in outcrop, consisting of sandy dolomite, sandy limestone, calcareous dolomite and calcareous sandstone (Veevers and Roberts, 1968). Siltstone, shale, sandstone and sandy limestone, identified as Burt Range Formation in Keep River 1 (Caye, 1969; Brown 1980) and in Weaber 1 (Garside, 1982), are here regarded as Bonaparte Formation.

Stratigraphic relationships: The Burt Range Formation conformably and disconformably overlies the Ningbing Group. In the type section, the lower contact with the Buttons Formation is conformable and lithologically gradational. Veevers and Roberts (1968) believed there was a hiatus between the two units, based primarily on Jones' (1968) ostracod-based determination of an early Famennian age for the Buttons Formation at its type section. Playford, G. (1982) and Jones (1985), however, determined a latest Devonian (Strunian) age for the Buttons Formation type section, suggesting that the two units are conformable. In the Carlton Shelf the contact with the Ningbing Group is poorly known. In the southeastern part of Ningbing Range, the Burt Range Formation disconformably overlies the Djilirri Limestone at the base of the Ningbing Group (Plate 3, section HH').

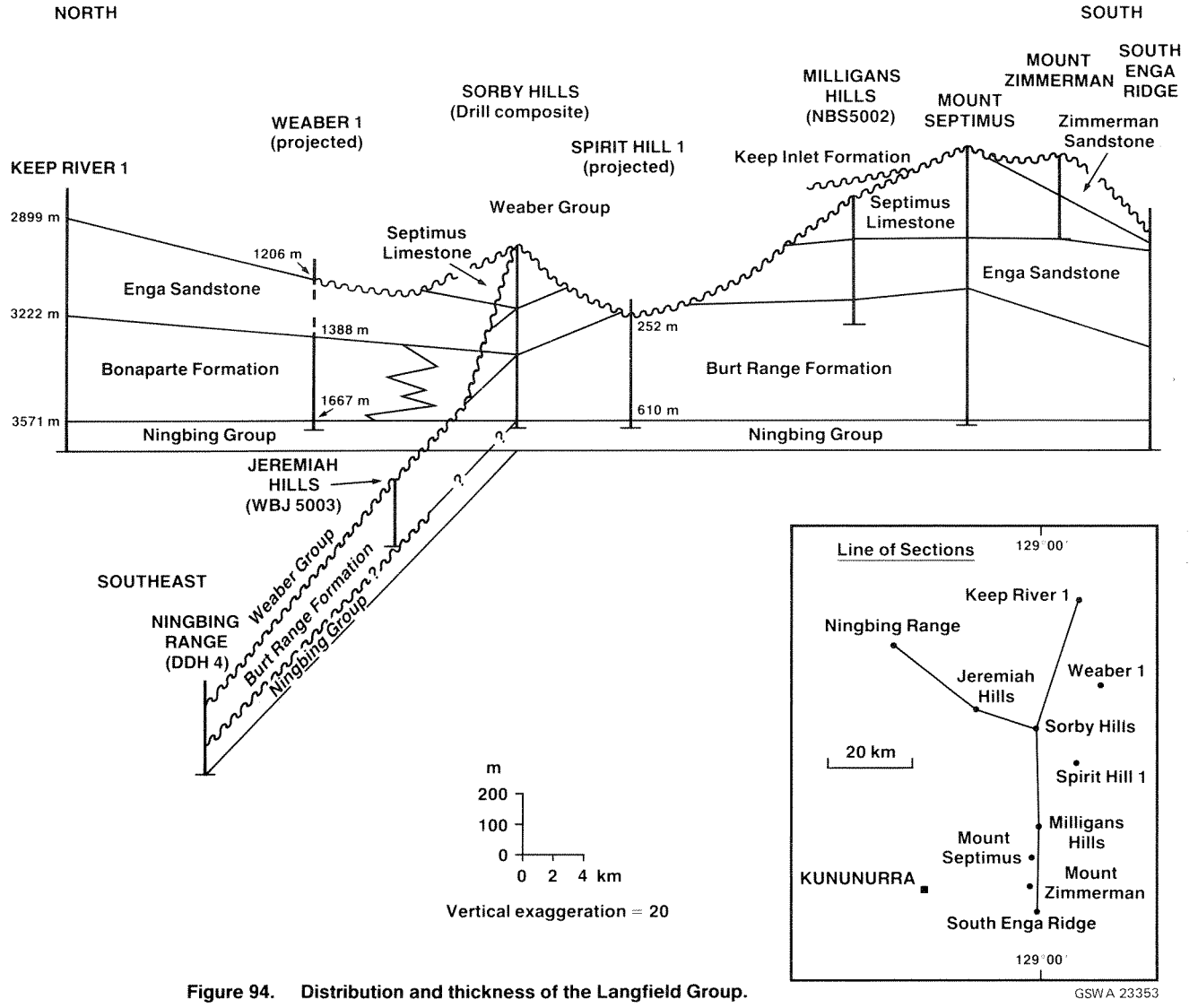

Figure 94. Distribution and thickness of the Langfield Group.

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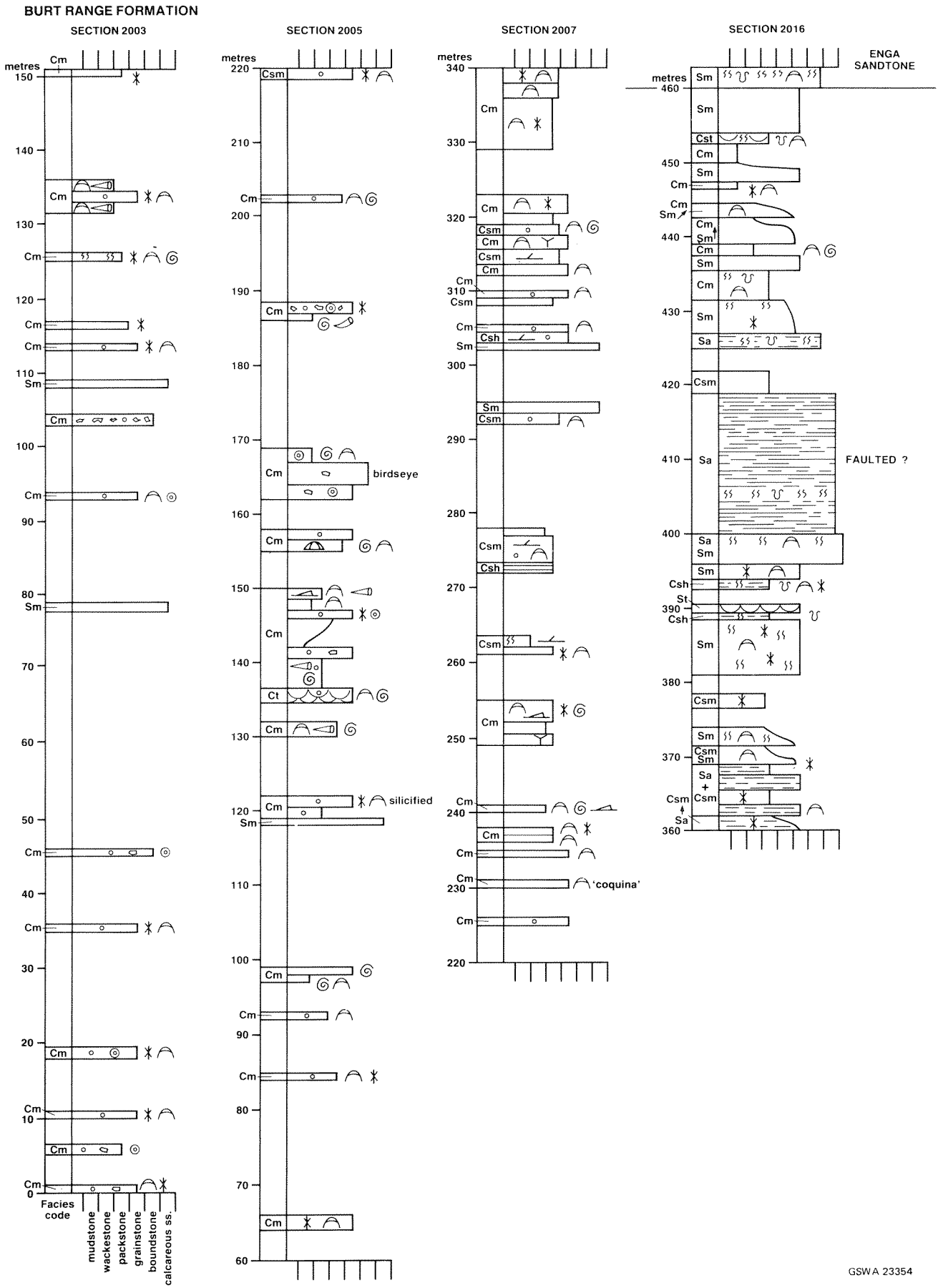

Figure 95. **Measured sections of the Burt Range Formation. Section locations shown in Figure 93, facies codes in Tables 1 and 8, key to symbols in Figure 3.**

The Burt Range Formation conformably underlies the Enga Sandstone. In the northern part of the Burt Range Amphitheatre, Veevers and Roberts (1968) inferred a local unconformable contact with the Enga Sandstone, as the brachiopods in the Burt Range Formation are the same as those in lower and middle parts of the type section. However, the unit is very sandy, similar to upper parts of the type section, and the contact is lithologically gradational and probably conformable.

In the subsurface the Milligans Formation overlies the Burt Range Formation with probable angular unconformity (Plate 1).

In the subsurface at Sorby Hills, the basal Sorby Dolomite Member lies conformably on the Buttons Formation but is separated from the overlying Knox Siltstone Member by a local unconformity. This break is due to uplift and subaerial exposure of the Sorby area over a brief interval of time. Deeply incised east-west erosional channels, with a relief of 20 to 30 m, have been mapped at this level by Elf Aquitaine Minerals Australia. The Knox Siltstone Member is overlain by the Gooseneck Member with another local unconformity separating the two units. Due to erosion at this level, and the transgressive character of this member, it also disconformably overlies the Cockatoo Group and Buttons Formation. Rowley and Lee (1986) suggest a lithological correlation of the Sorby Dolomite Member with the basal 120 m of the type section of Burt Range Formation, the Knox Siltstone Member with the interval 120 m to 250 m, and the Gooseneck Member with the interval 250 m to 460 m.

Distribution and thickness: The Burt Range Formation occurs principally in the Burt Range Shelf but is also known in the Carlton Shelf. It probably interfingers with Bonaparte Formation north of the Pincombe Inlier (Fig. 94). In the Burt Range Shelf most outcrop occurs between Eight Mile Creek and Enga Ridge. Isolated outcrops occur at Sorby Hills, Spirit Hill, and northeastwards along the basin margin to Flapper Hills and Legune. In the subsurface this unit has been encountered only in Spirit Hill 1. In the Carlton Shelf, isolated outcrops occur north of Jeremiah Hills and at Ningbing Range. Shallow mineral-exploration drill holes have intersected the unit in a belt between those points. It is not known from deep oil-exploration wells.

In the type section the formation is 460 m thick, which is the thickest known. At Sorby Hills the Sorby Dolomite Member is up to 100 m thick, the Knox Siltstone Member is up to 80 m thick, and the Gooseneck Member is up 100 m thick. But overall the formation generally does not exceed 220 m. To the south, at Enga Ridge, the formation is up to 240 m thick. In Spirit Hill 1, the unit is about 360 m thick. On the Carlton Shelf it has not been fully penetrated by drilling, but is at least 240 m thick north of Jeremiah Hills (Australian Aquitaine Minerals drill hole WBJ 5003), and 120 m has been intersected in the Ningbing Range (U.S. Steel drill hole DDH-4, Plate 3, section HH').

Fossils and age: Lower parts of the formation have a diverse fossil assemblage which includes stromatolites, brachiopods, crinoids, gastropods, corals, nautiloids, echinoids, and rare bryozoans. Upper parts of the formation contain mainly brachiopods, crinoids, and *Skolithos*. Veevers and Roberts (1968) also report conodonts, ostracods, trilobites, scolecodonts, bivalves, and wood fragments. The formation is dated as early to middle Tournaisian, based on conodonts (Druce, 1969) and brachiopods (Roberts, 1971).

ENGA SANDSTONE

Definition: The Enga Sandstone (Traves, 1955) is a unit of quartz sandstone with minor siltstone, shale and sandy limestone, lying conformably between the Burt Range Formation below and the Septimus Limestone above. The unit was included in the "Burt Range Series" by Matheson and Teichert (1948) and Reeves (1949). It was referred to as "Snowie Sandstone" by Traves (1949) and Noakes and others (1952), the name being derived from an informal synonym for Enga Ridge. Veevers and Roberts (1968) proposed the type section in the middle of Enga Ridge, about 4.5 km west-southwest of Langfield Point (base 15°48′50″S, 128°56′30″E; top 15°48′20″S, 128°57′00″E). The lower half of the formation is exposed in that section.

Lithology: The type section consists of well-sorted, fine- to medium-grained, white, quartz sandstone with minor calcarenite beds near the base (Veevers and Roberts, 1968). *Skolithos* is common particularly in the lower part of the formation. Lithologically the unit is transitional with the Burt Range Formation and the contact is marked by a prominent quartz-sandstone bed, packed with *Skolithos*, above which calcareous horizons are uncommon (Veevers and Roberts, 1968). This bed also coincides with a change in air-photo pattern, in which the prominent banding (benches) in the Burt Range Formation, changes to the smoother tones (fewer benches and rubble) in the lower part of the Enga Sandstone. In the subsurface the contact is difficult to determine.

Measured sections (Fig. 96) show there are at least three lithological divisions present, with the lowest two forming a coarsening-up sequence:

a) The basal 60 m consists of very fine- to medium-grained, very well-sorted, quartz sandstone with minor siltstone, and rare shale and sandy limestone. Marl occurs locally at the northern end of Enga Ridge (Veevers and Roberts, 1968). Sandstone is mainly parallel bedded or massive. Lamination, and planar and trough cross-bedding are minor. Siltstone is laminated and rarely massive. *Skolithos* is most abundant in this unit and often occurs in densely packed horizons (Fig. 97); bioturbated bedding planes are also common.

b) The overlying 40 m consists of fine- to medium-grained quartz sandstone with scattered granules and rare siltstone. Massive bedding and thin to medium parallel bedding are dominant. Trough and planar cross-bedding are common in the coarser sandstone.

c) The uppermost 55 m (section 2124, Fig. 98) consists mainly of fine- to coarse-grained,

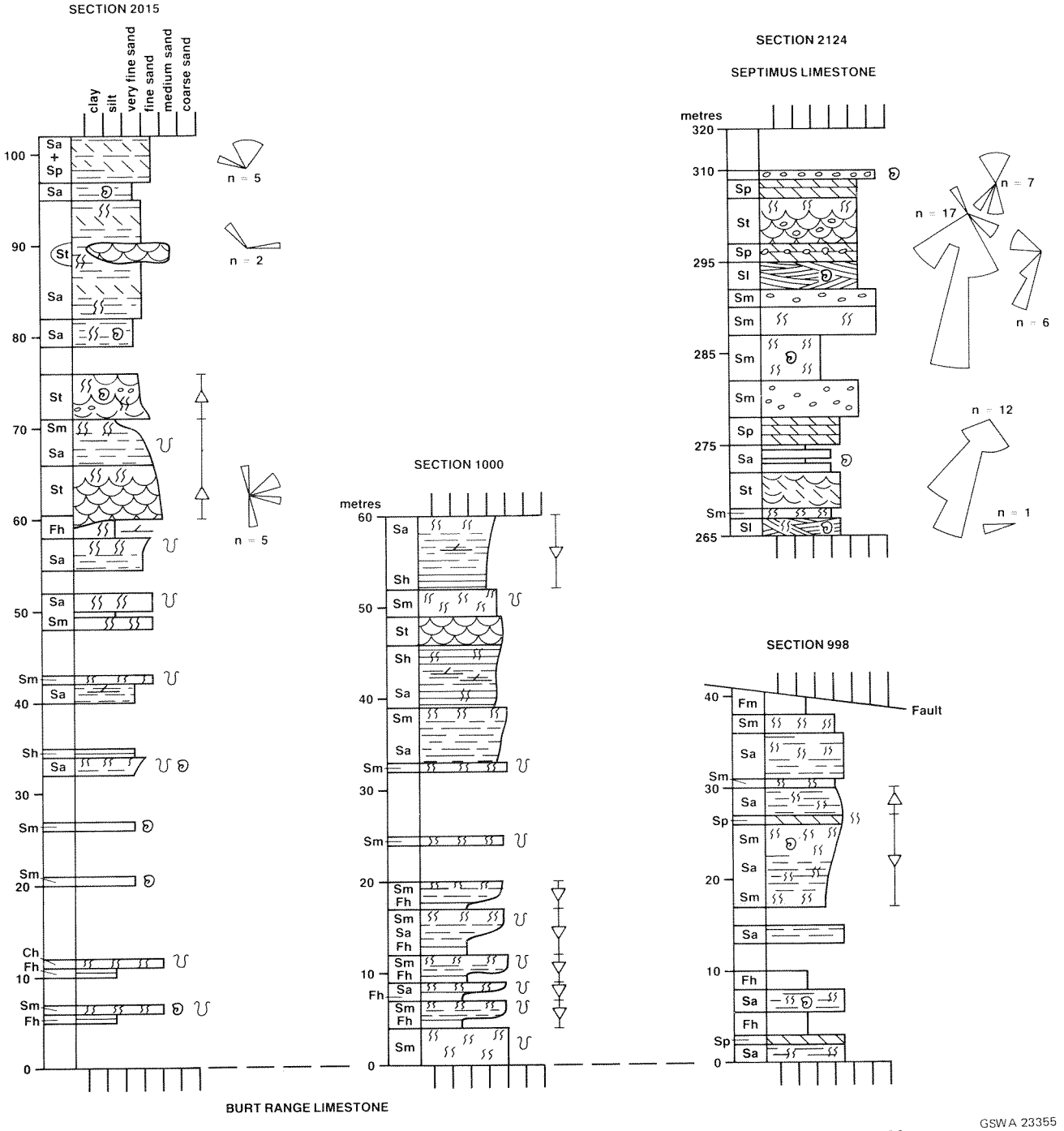

Figure 96. Measured sections of the Enga Sandstone. Section locations shown in Figure 93, facies codes in Tables 1 and 8, key to symbols in Figure 3.

well-sorted quartz sandstone with scattered granules, pebbles, and rare siltstone. Trough, planar, and low-angle cross-bedding, and massive bedding are common. Fifteen metres of very poor exposure, at the top of the section, possibly indicate the presence of marl or siltstone, similar to calcareous siltstone and shale between the Enga Sandstone and Septimus Limestone in Australian Aquitaine Minerals drill hole WBS 5002, near Milligans Hills.

At Sorby Hills, very fine- to fine-grained, ferruginized, quartz sandstone (with body fossils and *Skolithos*) is lithologically similar to the lower part of the type section and is here tentatively assigned to the Enga Sandstone.

In the subsurface, near Milligans (WBS 5002) and Sorby Hills, the sandstone is calcareous and dolomitic. Enga Sandstone in Keep River 1 (2899–3222 m) consists of 222 m of interbedded shale, calcareous sandstone, and minor siltstone, overlain by 100 m of calcareous oolitic sandstone with some interbedded shale and highly calcareous sandstone (Caye, 1969). In Weaber 1 (1206–1388 m) the unit consists of 102 m of interbedded siltstone and sandstone overlain by 80 m of interbedded sandstone and shale. The sandstone becomes coarser upwards. It is dolomitic, fine to medium grained and well sorted in the lower unit, and fine to coarse grained and well to poorly sorted in the upper unit (Garside, 1983). In both wells, these sequences were previously assigned to the Septimus Limestone (Caye, 1969; Brown, 1980; Garside, 1938). However, the lithology and general coarsening-up sequences suggest the unit is Enga Sandstone.

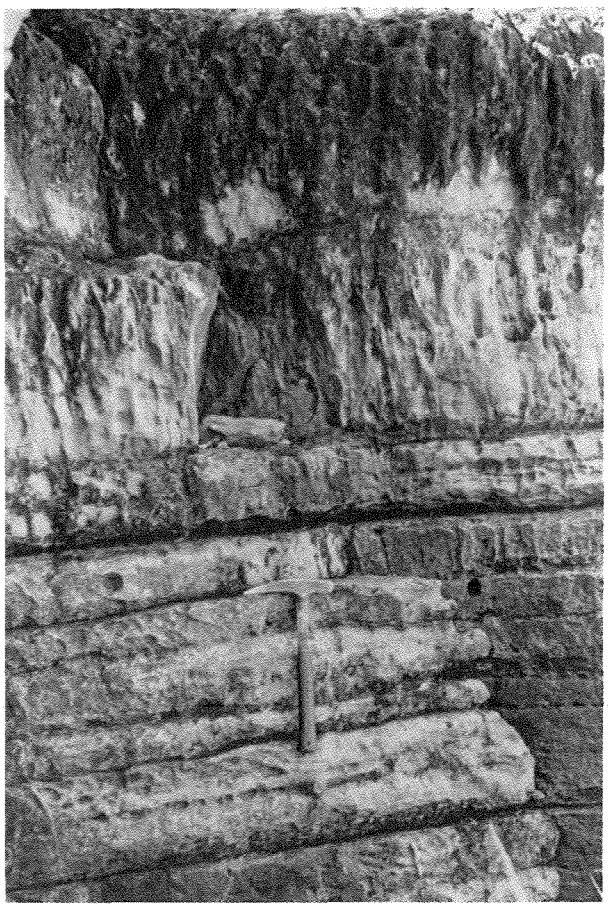

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Figure 97. Thin parallel-bedded sandstone (facies *Sa*) with some *Skolithos*, overlain by thicker beds of densely packed *Skolithos*. Enga Sandstone, 1.5 km southeast of the type section.

Stratigraphic relationships: In outcrop, the Enga Sandstone lies conformably between the Burt Range Formation, below, and the Septimus Limestone above. Throughout Burt Range the lower contact is lithologically gradational. As discussed above, Veevers and Roberts (1968) believed the lower contact was locally unconformable in the Burt Range Amphitheatre. The contact with Septimus Limestone is not exposed, but if the topmost unexposed 15 m of section 2124 is marl or siltstone, then the contact is lithologically gradational. In this section, Veevers and Roberts (1968) inferred a disconformity, as brachiopods in the overlying Septimus Limestone occur in the uppermost part of the Septimus Limestone in the type section. However, conodonts from the lower part of the Septimus Limestone and the base of the Enga Sandstone are from the same zone (Veevers and Roberts, 1968) suggesting there is little likelihood of a hiatus between the two units. In Keep River 1 and Weaber 1, the Enga Sandstone conformably overlies the Bonaparte Formation, while it is probably unconformably overlain by the Milligans Formation.

Distribution and thickness: The Enga Sandstone is known only from the Burt Range Shelf. Extensive outcrops occur in the Burt Range. Isolated outcrops occur at Milligans Hills, Sorby Hills, and several localities in the Northern Territory. In the subsurface, it extends to Weaber 1 and at least as far north as Keep River 1.

The type section is 148 m thick, and Veevers and Roberts (1968) believed the unit totalled about 159 m. The unit is here estimated to be about 320 m thick; the additional 160 m (between sections 2015 and 2124) crops out on the dip slope of the cuesta which forms Enga Ridge. To the north, the unit thins to about 160 m at Sorby Hills then thickens to 182 m in Weaber 1 and 320 m in Keep River 1.

Fossils and age: Body and trace fossils occur throughout the formation but are most abundant in the lower part. *Skolithos* is common, often

forming densely packed beds. Body fossils consist mainly of bivalves and brachiopods. Gastropods (Thomas, 1962), bryozoans, trilobites, ostracods (Veevers and Roberts, 1968), foraminifers (Mamet and Belford, 1968), and crinoids and algae (Caye, 1969; Mamet and Roux, 1983) are also present. A mid-Tournaisian age (Tn2) is indicated by conodonts (Druce, 1969) and brachiopods (Roberts 1971).

SEPTIMUS LIMESTONE

Definition: The Septimus Limestone consists of limestone and sandy limestone with minor marl and calcareous sandstone. The unit was initially examined by Matheson and Teichert (1948). It was termed "Mount Septimus Series" by Reeves (1949), then "Mount Septimus Limestone" by Noakes and others (1952), and was later amended

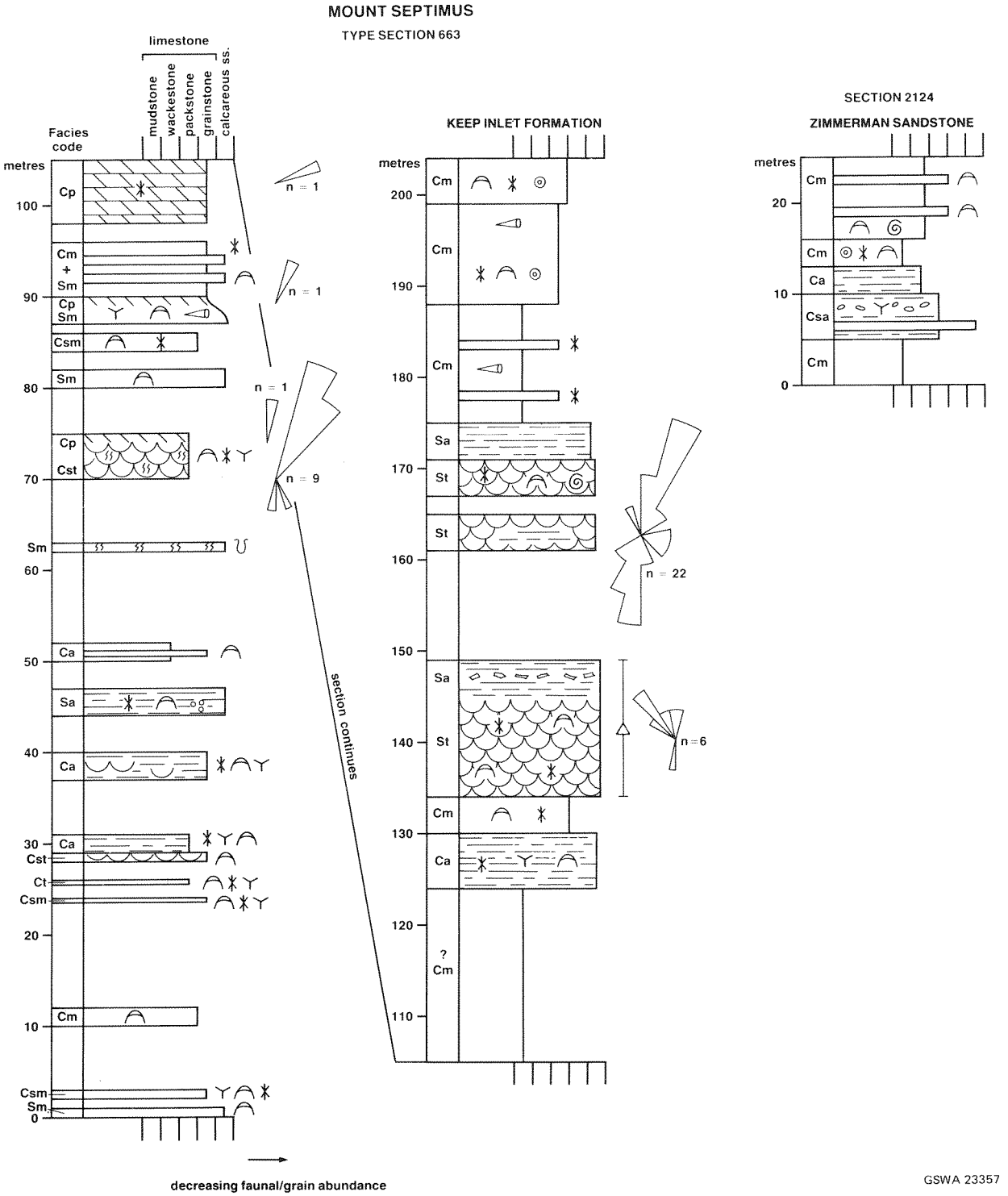

Figure 98. Measured sections of the Septimus Limestone. Location of sections in Figure 93, facies codes in Tables 1 and 8, key to symbols in Figure 3.

by Traves (1955). Veevers and Roberts (1968) designated the type section on the northwest flank of Mount Septimus (base 15°42′30″S, 128°58′40″E; top 15°42′50″S, 128°59′10″E).

Lithology: The type section (Fig. 98, section 663), consists of 105 m of limestone, sandy limestone, and minor calcareous sandstone, overlain by 99 m of limestone, calcareous sandstone, and marl. In the lower unit, limestone and sandy limestone are mainly packstone and grainstone, with minor wackestone. Thin to medium parallel and trough cross-bedding, thick planar cross-bedding (Fig. 99), and massive bedding are present. Fine- to coarse-grained quartz sand is scattered throughout the limestone. Calcareous sandstone beds are fine to medium grained, well sorted, and massive bedded. Calcareous grains consist of abraded fragments of brachiopods, crinoids, and bryozoans, with minor corals and peloids. Many beds are dominated by a particular grain type, and some contain unfragmented brachiopods. *Skolithos* is also present. In the upper unit the limestone consists of packstone and grainstone, and it may contain scattered fine- to coarse-grained sand and granules. Calcareous mudstone or marl are also common. The limestone is massive with minor parallel bedding. Calcareous sandstone is fine to coarse grained, well sorted, thin to medium trough cross-bedded and parallel bedded. It also contains rare intraformational breccias (Fig. 100). Calcareous grains consist mainly of brachiopods and crinoids, with minor bryozoans, corals, gastropods, oncolites, and intraclasts. Unfragmented fossils occur in mudstone and marl.

At southern Enga Ridge, the Septimus Limestone consists of 25 m of silty and sandy mudstone and wackestone (Fig. 98, section 2124), with minor brachiopod packstone and calcareous sandstone. The sandy limestone at 8 m, in that section, contains scattered quartzite pebbles, similar to those near the top of the underlying Enga Sandstone. Other detailed sections have not been measured, but lithologies at Mount Septimus and Mount Zimmerman are similar to the type section. An isolated outcrop, 3 km east of Mount Septimus, was described by Veevers and Roberts (1968) as dolomitic and calcareous sandstone, and quartz sandstone.

In the subsurface 3 km south of Milligans Hills (Australian Aquitaine drill hole WBS 5002), the Septimus Limestone consists of 40 m of interbedded calcareous siltstone and shale, overlain by 40 m of packstone and grainstone, followed by 60 m of sandy limestone and sandstone.

Stratigraphic relationships: The Septimus Limestone lies conformably between the Enga Sandstone, below, and the Zimmerman Sandstone, above, in the Burt Range. In the type section the unit is overlain with angular unconformity by the Keep Inlet Formation, and the base is unexposed. Pebbles and marls, or siltstones, in both the Enga sandstone and lower part of the Septimus Limestone in section 2124 (Fig. 98), indicate a gradational contact. Conodonts from the base of the Enga Sandstone and lower part of the Septimus Limestone are from the same zone (Veevers and Roberts, 1968). The Septimus Limestone and

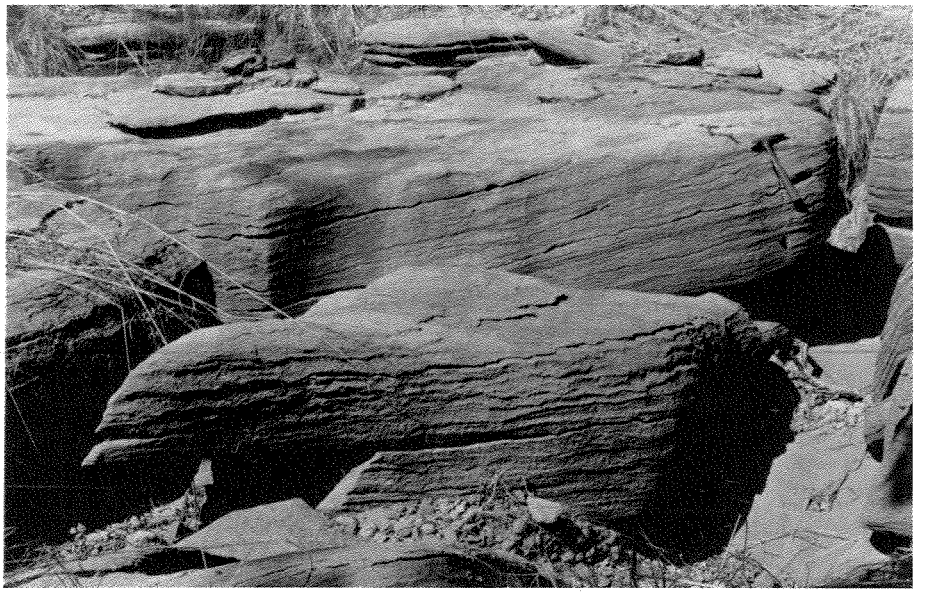

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Figure 99. Thick set (0.7 m) of low-angle planar cross-bedded packstone. The top surface is a bedding plane. Septimus Limestone type section.

Zimmerman Sandstone are lithologically dissimilar, but are probably conformable.

Using faunal assemblages, Veevers and Roberts (1968) inferred local disconformable contacts with adjacent formations. Thomas (1962) identified four faunal assemblages in the Septimus Limestone type section, of which, assemblage 'c' occurs 30–40 m below the top. Veevers and Roberts (1968) also found this assemblage in section 2124 (Fig. 98) just above the Enga Sandstone and, assuming it was a time marker, inferred a disconformity. However, the two units are here considered to be gradational with either the assemblages being facies dependent (also suggested by Roberts, 1971, p. 26), or with the Enga Sandstone correlating with most of the Septimus Limestone in the type section. The latter is unlikely as it requires carbonate and clastic deposition in a small area. Above assemblage 'c' the Septimus Limestone has an irregular thickness, attributed by Veevers and Roberts (1968) to erosion prior to deposition of the Zimmerman Sandstone.

Distribution and thickness: The Septimus Limestone occurs only in the Burt Range Shelf, mainly in central Burt Range. Isolated outcrops also occur 3 km east of Mount Septimus and in the Spirit Hill area (Thomas, 1962). Shallow boreholes have intersected the unit at Milligans Hills and as far north as Sorby Hills. Calcareous sandstone in Keep River 1, assigned to Septimus Limestone by Caye (1969) and Brown (1980), is probably Enga Sandstone (Fig. 94).

The type section exposes about 204 m but the base is not exposed and the unit is probably about 300 m thick. A greater thickness was probably deposited, as erosion occurred prior to deposition of the Keep Inlet Formation. The unit thins rapidly to the south, and 9 km from the type section it is 25 m thick.

Fossils and age: The fauna consists mainly of brachiopods and crinoids, with minor corals. Molluscs, trilobites, blastoids, ostracods, conodonts, echinoids, and sponges have also been recorded (Thomas, 1962). A Tournaisian age is indicated by conodonts (Druce, 1969) and brachiopods (Roberts, 1971). The correlation of conodont faunas in eastern Australia with those in Western Australia suggests the Septimus Limestone is Middle Tournaisian, Tn 2, (Mory and Crane, 1982).

ZIMMERMAN SANDSTONE

Definition: The Zimmerman Sandstone (Veevers and Roberts, 1968) consists of sandstone, with minor siltstone and shale. These conformably overlie the Septimus Limestone and are overlain with angular unconformity by the Keep Inlet Formation. The type section is on the western scarp of Mount Zimmerman (base 15°46′40″S, 128°58′10″E; top 15°46′50″S, 128°58′20″).

Lithology: The type section (Fig. 101) consists of white and brown quartz sandstone with minor siltstone, shale, and brown quartz wacke. Shale may form a major portion of this unit if it underlies the numerous poorly exposed zones. The

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Figure 100. Intraformational breccia, Septimus Limestone. The host rock, exposed near the hammer head, is calcareous sandstone.

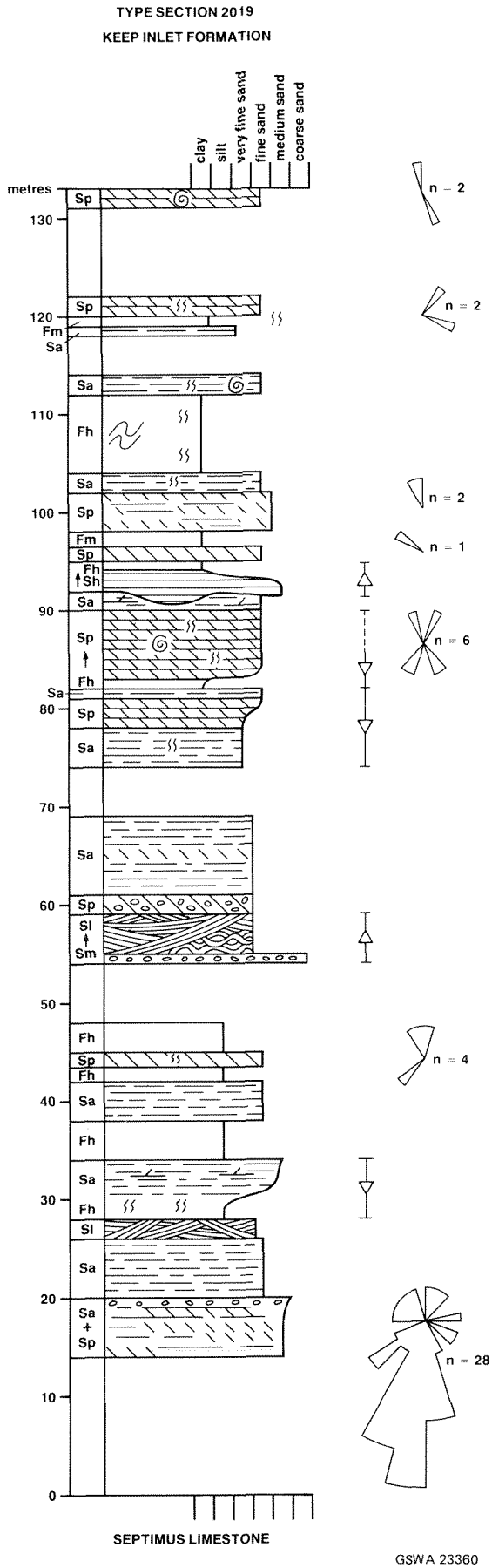

Figure 101. Type section, Zimmerman Sandstone. Location shown in Figure 93, facies codes in Tables 1 and 8, key to symbols in Figure 3.

sandstone is very fine to medium grained, moderate to very well sorted, texturally immature to submature, and may be bimodal and texturally inverted, with rounded quartz grains and a high proportion of clay matrix. The quartz wacke is generally coarser and more poorly sorted than the quartz sandstone, and may contain scattered granules. Thin to medium parallel bedding (Fig. 102) and planar cross-bedding is dominant and lamination is minor. Siltstone and shale are laminated or massive and may be bioturbated. Minor calcareous sandstone occurs in the Burt Range Amphitheatre.

Stratigraphic relationships: In the type section, the Zimmerman Sandstone conformably overlies the Septimus Limestone, and is overlain with angular unconformity by the Keep Inlet Formation.

Distribution and thickness: The Zimmerman Sandstone is known only from outcrops in the central Burt Range, on the Burt Range Shelf. The type section is the thickest known at 133 m. Thinning to the north and south is probably due to erosion, prior to deposition of the Keep Inlet Formation. Veevers and Roberts (1968) documented a channel, 25 m deep, in the Zimmerman Sandstone filled with Keep Inlet Formation conglomerate. Six kilometres north of the type section, the Zimmerman Sandstone has been completely eroded so that Keep Inlet Formation rests directly on Septimus Limestone. Four kilometres south of the type section only 25 m of section are present.

Fossils and age: Uncommon body fossils occur mainly as moulds, and include brachiopods, bivalves, bryozoans, and crinoids. *Rhizocorallium* and unidentified trace fossils are also present. The brachiopods indicate a late Tournaisian age (Roberts, 1971).

FACIES ANALYSIS OF THE LANGFIELD GROUP

The Langfield Group consists mainly of limestone, sandstone, and minor shale. A number of facies and facies associations have been recognized, and many are common to several formations. Shallow-marine deposition is indicated by fossils and the texture of both carbonate and clastic sediments. Thirteen facies have been recognized in the Langfield Group. Their description and distribution within formations are given in Tables 8 and 9.

Facies *St*, in the Enga Sandstone, occurs in fining-up sequences with eroded bases, and probably represents sinuous-crested dunes deposited in tidal channels. North-south directed

TABLE 8. LIMESTONE AND SANDY LIMESTONE FACIES, LANGFIELD GROUP

	FACIES	*BURT RANGE FORMATION*	*SEPTIMUS LIMESTONE*
Cm *Csm*	Massive limestone, Sandy massive limestone	Mudstone to boundstone; thin to medium beds; may cap facies *Sm;* rare intraformational breccias, bioturbation, ripples.	Mudstone to grainstone; thin to very thick beds (max. 19m)
Ct *Cst*	Trough cross-bedded limestone, Sandy trough cross-bedded limestone	Occurs rarely; grainstone; Beds <2m thick, sets <0.3m; minor *Skolithos*	Packstone, grainstone, scattered medium to coarse sand and granules; beds <3m thick, sets 0.1–0.3m; minor bioturbation; palaeocurrents unimodal to north-northeast
Ch *Csh*	Laminated limestone Sandy laminated limestone	Occurs rarely; packstone, grainstone; beds <2m thick; minor ripples and *Skolithos;* rare intraformational clasts	
Cp	Planar cross-bedded limestone		Packstone, grainstone; beds <7m thick, sets <2m, foresets dip 4–6°
Ca	Parallel-bedded limestone		Wackestone to grainstone; beds <6m thick; rare trough cross-bedding

cross-beds indicate that the coastline was oriented east-west; land is assumed to have been to the south. Trough cross-bedded limestones (facies *Ct*) have a similar palaeocurrent orientation, indicating that they are also tidal-channel deposits. Palaeocurrent distributions are often unimodal, to the north or south, indicating a dominance of ebb and flood bed forms, respectively. Thin beds of facies *St* and *Ct*, occurring within shoreface facies, are probably also shoreface deposits.

Cross-beds in facies *Sp* are directed parallel to tidal-channel cross-bedding, suggesting that they represent straight-crested dunes deposited in tidal deltas. Unimodal and bimodal palaeocurrent distributions reflect ebb or flood dominance or tidal-flow symmetry, respectively.

Large planar cross-beds can occur in deep tidal channels and on the shoreface and foreshore (Inden and Moore, 1983). Low-angle cross-beds in facies *Cp* are directed offshore and overlie tidal

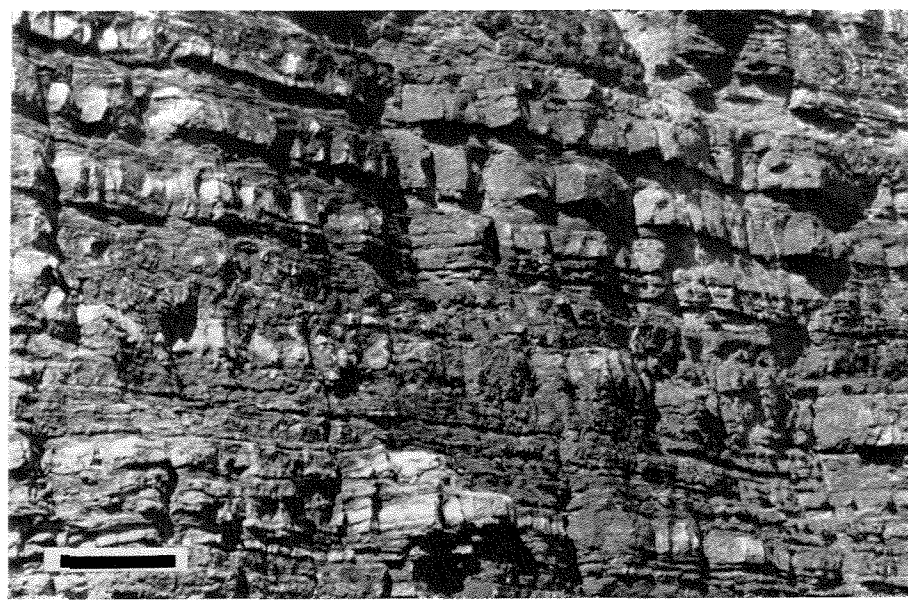

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Figure 102. Thin to medium interbeds of parallel-bedded quartz arenite (prominent beds) and quartz wacke (facies *Sa*). Zimmerman Sandstone type section. Scale bar is 0.5 m.

channels (facies *Ct*), suggesting that they formed as large sandwaves on an upper shoreface or as beach accretion ridges. Coarse-grained, poorly sorted, massive sandstone (facies *Sm*) may be beach deposits, but as they are commonly associated with tidal channels and deltas, they may also represent lag deposits.

Other facies were deposited as plane beds or undulating bed forms on a shoreface, under both low-energy (*Sa, Sh, Ch,* and *Ca*) or relatively high-energy conditions (*Sl* and *Sh*). Slow continuous deposition probably allowed extensive bioturbation in fine-grained facies *Sm*. Beds of densely packed *Skolithos* represent either temporary still-stands on the shoreface (facies *Sa*), or tidal channel abandonment (facies *St*). Storm deposition is represented by the immature quartz wacke lithology and textural inversions in many Zimmerman Sandstone facies, together with massive sandstone beds (*Sm*) containing eroded bases and escape burrows. Intraclasts in the Septimus Limestone (facies *Sa*) are identical to the host rock, suggesting storm erosion of beachrock.

Massive limestones (facies *Cm*) are typically found in subtidal environments (Enos, 1983). Deposition occurred above wave base where the energy was high enough to winnow the sediment (packstone, grainstone), but not high enough to produce bed forms. intense burrowing may also produce homogenized massive sediment (Enos, 1983). Laminated and stromatolitic boundstones were probably deposited in intertidal-supratidal environments. Clasts in the intraformational breccias are microbial boundstones indicating storm reworking of intertidal-supratidal deposits. Limestones which cap calcareous sandstone beds (*Sm*) represent the return of relatively low-energy carbonate deposition, after a period of high-energy siliciclastic input.

Siltstone/shale facies (*Fh* and *Fm*) represent quiet-water suspension deposition. The interbedding of these facies with shoreface sandstones, in both the Enga and Zimmerman Sandstones, suggest that they represent offshore deposition below wave base. However, the facies also occur with tidal deltas (facies *Sp*) in the Zimmerman Sandstone, suggesting a possible lagoonal origin.

Facies associations

On the basis of lithology, facies, and facies sequences, eleven facies associations are recognized (Table 10).

Facies association 1 (FA 1): This consists of massive limestone (*Cm*) in a very thick, coarsening, or shoaling-up sequence between 175 m and 204 m in the type section of Septimus Limestone (Fig. 98, Table 10). The thick limestone beds vary from mudstone at the base of the sequence, through packstone, to grainstone at the top. Unfragmented crinoids and corals occur throughout, but brachiopods and oncolites, (nucleating on shell fragments) occur mainly in grainstone.

This facies association was probably deposited in a quiet-water middle-shelf environment. The lack of bedding structures indicates subtidal deposition. Muddy carbonates are common in middle-shelf environments, and grainstone shoals

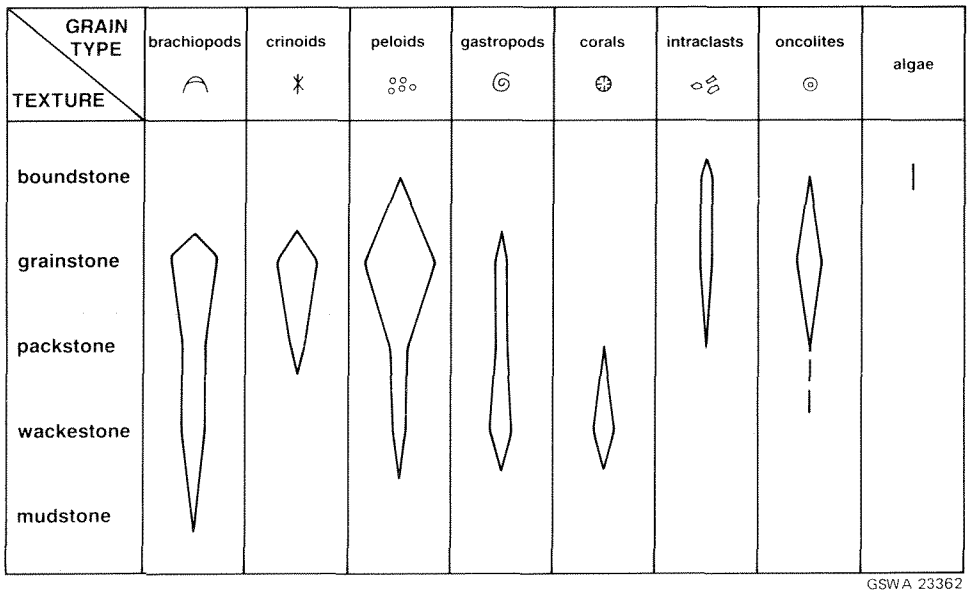

Figure 103. Limestone texture and the variation and relative abundance of major carbonate-grain types within FA 2, Burt Range Limestone.

TABLE 9. SANDSTONE AND SILTSTONE/SHALE FACIES, LANGFIELD GROUP

FACIES	*BURT RANGE FORMATION*	*ENGA SANDSTONE*	*SEPTIMUS LIMESTONE*	*ZIMMERMAN SANDSTONE*
SANDSTONE:				
St Trough cross-bedded; fine to medium quartz sandstone, minor coarse sand and granules		Beds and lenses 4–6 m thick, sets <0.4 m, fining-up sequences <5 m; eroded and non-eroded base; scattered fossil fragments, *Skolithos* horizons; unimodal palaeocurrents, to south, north and east	Calcareous; beds 3–5 m, max 8 m; scattered fossils and *Skolithos*, overturned foresets; minor *Sa, Sp;* palaeocurrents unimodal to northwest, and bimodal north-northeast to south-southeast	
Very fine grained	Calcareous; beds <1 m, sets <0.2 m			
Sp Planar cross-bedded; very fine to fine quartz sandstone coarse sand and granules; also quartz wacke (Zimmerman Sandstone)		Beds 2–3 m thick, sets <0.5 m; non-eroded base; unimodal and bimodal palaeocurrents to north and south		Beds <7m, sets 0.1–0.5 m; scattered body and trace fossils, *Skolithos;* minor *Sa;* asymmetric bimodal palaeocurrents mainly to south, also polymodal
Sm Massive; medium to coarse quartz sandstone, moderate to poor sorting, scattered granules, pebbles. Quartz wacke in Zimmerman Sandstone very fine to fine grained, well sorted		Beds 0.5–4 m; minor body fossils, facies *Sh, Sa, Sl*		Beds 0.5 m, possibly fines-up into *Sl*
	Calcareous and non-calcareous; beds 2–5 m, max. 7 m; brachiopod and crinoid fragments, bioturbated; interbedded and gradational with *Cm*	Silty; beds 0.2–4.0 m; totally bioturbated (*Skolithos*); minor eroded base, escape burrows, facies *Sa*	Calcareous; beds <2 m; minor bioturbation and body fossils, *Skolithos;* interbedded with facies *Cp, Cm*	

Sa	Parallel-bedded; very fine to medium quartz sandstone, well sorted, (minor quartz wacke, Zimmerman Sandstone), minor shale and silty sandstone interbeds	Locally calcareous; beds 1–3 m, 19 m max. *Skolithos* beds, undifferentiated, bioturbation, brachipod and crinoid fragments; some highly calcareous tops	Rarely calcareous; beds 1–5 m, max 13 m; diverse body and trace fossils, massed *Skolithos*; minor rippled siltstone, facies *Sp, Sh, Sm,* coarsening and thickening-up sequences	Calcareous; beds 3–4 m; intraclast breccia, clasts <15 cm	Beds 0.5–4.0 m, 8 m max; diverse body and trace fossils; minor ripples, facies *Sm, Sp, Sl*
Sl	Low-angle cross-bedded; fine to medium quartz sandstone, well sorted		Beds 2–3 m; bioturbated, some body fossils; overlies *Sm*		Beds 2–4 m, sets 0.1–0.3 m; transitional with *Sm* and *Sa*
Sh	Laminated; very fine to medium quartz sandstone and wacke (Zimmerman Sandstone), well sorted.	Calcareous; beds 1–2 m; transitional with *Csh*	Beds 2 m; horizontal burrows, locally abundant body fossils; ripples		Beds 3 m; eroded and non-eroded base; coarsening-up and fining-up cycles with *Fh*
SHALE:					
Fh	Laminated; siltstone, very fine sandstone		Beds 0.5–3 m; horizontal and complete bioturbation, locally abundant fossil fragments, articulated fossils; minor ripples, flasers, very thin *St,* wackestone, packstone; rare 0.5 m lens fine sandstone		Interbedded with sandstones, transitional with *Sh;* horizontal bioturbation; minor ripples, contorted beds; silty sandstone and shale lenses
Fm	Massive; shale and silty shale		Beds 2 m		Beds 1–2 m; some sandy lenses, bioturbated; gradational with *Sa*

TABLE 10. FACIES ASSOCIATIONS OF THE LANGFIELD GROUP

FACIES ASSOCIATION		LITHOLOGY: Limestone (m, w, p, g, b, sandy)	LITHOLOGY: Calcareous sandstone	LITHOLOGY: Sandstone	FACIES: Major	FACIES: Minor	FOSSILS & CALCAREOUS GRAINS (Decreasing abundance)	SEQUENCES	STRATIGRAPHIC POSITION		
Mainly limestone	1		–	–	Cm			shoaling cycles <25m thick		*Burt Range Formation (Sections 2003 & 2005)*	175-204m
	2		minor minor	–	Cm Cm	Sm Ct Sm (/rare)	laminar algae	thin shoaling cycles (few metres)	100-190 0-100		
	3	(rare)	minor	–	Cm Cm Csm	Csm Csh Sm	rare	–	190-260 260-320		*Sypinus limestone 663)*
	4		minor	–	Ca Csm Sm Sa	Cm Cst Ct		–			0-70
	5		minor	–	Cp Sm	Cm Cst Csm		–			70-105
Mixed limestone and sandstone	6		common	–	Cm Csm Sm	Sa Csh / St		–	320-395		
	7		common	–	St Cm	Sa Ca		shoaling up cycles <25m thick			105-175
	8		common	Common	Sa Sm Cm	Csm Cst			395-440		
Sandstone	9	*common siltstone and shale*	rare	common	Sa Fh Sp	Sl Sh Sm Fm	undifferentiated body and trace fossils	CU& FU: Fh ↔ Sh (3-6m) shoaling sequences up to 38m thick	0-132 (total)	*Zimmerman Sandstone*	
	10	*minor siltstone and shale*	minor	common	Sm Sa	Fh Sh Sp St Fm Ch	& undifferentiated body fossils	CU: Fh → Sh, Sa → Sm (2-8m)			0-60m
	11	–		common	Sa Sm St Sp	Sl	& undifferentiated body fossils	FU: St → Sa (10m)			60-102 uppermost 55m

may also occur (Wilson and Jordan, 1983). The coarsening-up sequence may represent the development of such a shoal.

Facies association 2 (FA 2): This association occurs between 0 m and 190 m in the Burt Range Formation. It consists of massive limestone (*Cm*), rare trough cross-bedded limestone (*Ct*), and massive calcareous sandstone (*Sm*). Massive limestone varies from mudstone to grainstone, with minor boundstone and intraformational breccia. This association has the greatest diversity of grain types. Corals and gastropods occur mainly in wackestone (Fig. 103). Peloids, crinoids, brachiopods, and oncolites dominate the grainstones. Boundstone is dominated by intraclasts and laminated, fenestral, and domed stromatolites (Veevers and Roberts, 1968). Clasts in intraformational breccia consist of laminated stromatolites. A shoaling-up sequence at 142–147 m shows partitioning of grain types. The sequence consists of basal unfossiliferous mudstone, brachiopod-crinoid packstone and grainstone, and uppermost peloid-crinoid packstone and grainstone, and uppermost peloid-crinoid-oncolite grainstone. The textural variation of limestones and faunal distribution in the rest of this association suggest that it may contain other shoaling-upward sequences.

The variable limestone texture probably reflects sea-floor palaeotopography, with deposition occurring on a restricted shelf. The impoverished fauna in mudstone indicates low-energy lagoonal deposition, with grainy sediments being deposited in higher energy, shallower, subtidal areas. Stromatolitic boundstones indicate intertidal-supratidal deposition and breccias represent storm reworking of these areas. Shoaling-up cycles with high-energy subtidal units are produced by the shallowing of lime-sand bodies to form offshore barriers (James 1979).

Facies association 3 (FA 3): This consists mainly of massive limestone (*Cm*) with lesser sandy limestone (*Csm*) and occurs between 190 m and 320 m in the Burt Range Formation. Packstones and grainstones may contain scattered fine- to medium-grained quartz; also, carbonate grain types are more restricted than in FA 2. Peloids dominate the sequence between 190 m and 225 m, while brachiopods dominate between 225 m and 260 m; both are equally abundant between 260 m and 320 m. Laminated sandy limestone (*Csh*) and massive, fine- to medium-grained, calcareous sandstone (*Sm*) are minor.

Deposition occurred on an open carbonate shelf, possibly associated with a barrier. Massive limestones and the lack of mud indicate deposition in a persistently high-energy subtidal environment. Restricted fauna and the dominance of thick sequences by peloids and brachiopods suggest environmental stress, possibly due to a barrier consisting of shoreface deposits of massive calcareous sandstone and laminated carbonate.

Facies association 4 (FA 4): This consists of parallel-bedded limestone (*Ca*), with lesser parallel-bedded and massive calcareous sandstone (*Sa* and *Sm*) and massive sandy limestone (*Csm*). It occurs between 0 m and 70 m in the type section of

Septimus Limestone. Limestones are packstones and grainstones; and sandy limestone contains scattered fine- to coarse-grained quartz. Calcareous grains consist mainly of brachiopods, crinoids, and bryozoans, with minor peloids. *Skolithos* burrows are also present. Minor facies include massive limestone (*Cm*), and trough cross-bedded limestone and sandy limestone (*Ct* and *Cst*).

This association was probably deposited on a calcareous shoreface. Relatively high-energy calcareous and clastic deposition is indicated by parallel and trough cross-bedding. Lower energy shoreface to offshore deposition is indicated by massive beds.

Facies association 5 (FA 5): This consists mainly of thick planar cross-bedded limestone (*Cp*) with lesser massive calcareous sandstone (*Sm*). It occurs between 70 m and 105 m in the type section of Septimus Limestone. The limestones are mainly packstones and grainstones with scattered medium- to coarse-grained quartz. Calcareous sandstone is fine to medium grained. Major grain types include brachiopods, crinoids, and bryozoans, with minor corals. Minor facies include massive limestone and sandy limestone (*Cm* and *Csm*), and trough cross-bedded sandy limestone (*Cst*).

Facies association 5 is interpreted as a high-energy shoal or barrier complex. Trough cross-bedded calcareous sandstones are interpreted to be tidal-channel deposits, because the palaeocurrent orientation (Fig. 98) is the same as in tidal channels higher in the sequence. Thick planar cross-beds occur above the tidal channels and have a similar orientation, indicating that they are probably beach accretionary beds. Massive limestone and sandstone facies were deposited in subtidal areas and on the shoreface.

Facies association 6 (FA 6): This consists mainly of massive limestone (*Cm*), sandy limestone (*Csm*), and calcareous sandstone (*Sm*), and occurs between 320 m and 395 m in the Burt Range Formation (Fig. 95). Limestones are packstones and grainstones, and bioclastic grains include brachiopod and crinoidal debris. *Skolithos* bioturbation is common in calcareous sandstone. Minor facies include parallel and trough cross-bedded calcareous sandstone (*Sa* and *St*) and laminated sandy limestone (*Csh*). Facies *Sm* often has highly calcareous tops.

This association was probably deposited in a transition zone between carbonate shelf and clastic shoreface. The textures in massive limestone and sandy limestone indicate relatively high-energy shelf deposition. Facies *Sa* and *Sm* represent shoreface deposition. Thin interbedding and gradational transitions, between carbonates and clastics, indicate that deposition occurred near the limit of clastic influence. Facies *Csh* and *St* were deposited on the shoreface as high-energy planar beds and dunes, respectively.

Facies association 7 (FA 7): This consists mainly of trough cross-bedded calcareous sandstone (*St*) and massive limestone (*Cm*), and occurs between 105 m and 175 m in the type section of Septimus Limestone. Minor facies include parallel-bedded calcareous sandstone and limestone (*Sa* and *Ca*). Facies *St* contains fine- to medium-grained quartz sand with scattered very coarse sand and granules. Palaeocurrent distributions are unimodal to the northwest and bimodal north-south (Fig. 98). Facies *Cm* and *Ca* vary from wackestone to grainstone. Facies *Sa* is fine grained and contains an intraclast breccia, and overlies facies *St* in a fining-upward sequence.

Facies association 7 is interpreted to be a barrier system dominated by clastic-filled tidal channels and offshore or shelf carbonates. Carbonates were deposited on a shoreface (*Ca*) and in subtidal environments (*Cm*), under both low-energy (wackestone) and high-energy conditions (packstone and grainstone). Tidal channels (*St*) were oriented north-south and tidal flow was either symmetrical or ebb-oriented to the north. Facies *Sa* represents shoreface deposition, although the intraformational breccias suggest some may be foreshore deposits. The vertical arrangement of facies in this association suggests that there are three shoaling cycles, each 19–25 m thick. They consist of shelf-shoreface-tidal channels, reflecting barrier progradation.

Facies association 8 (FA 8): The association consists mainly of parallel-bedded and massive sandstone and calcareous sandstone (*Sa* and *Sm*), and massive limestone (*Cm*). It occurs between 395 m and 460 m in the Burt Range Formation (Fig. 95). Minor facies include trough cross-bedded and massive sandy limestone (*Cst* and *Csm*). Fauna consist mainly of brachiopods, crinoids, gastropods,and *Skolithos*. Sandstone is very fine to fine grained, and limestone varies from mudstone to packstone. Some massive sandstones fine upwards into limestone.

Facies association 8 is interpreted as shoreface deposits with minor offshore (shelf) carbonates. Low-energy shoreface deposits include facies *Sa* and *Sm*, and muddy textures in facies *Cm* indicate relatively low-energy offshore deposition. Fining-up sequences were probably formed by initial rapid deposition of clastics in the

shoreface/offshore transition zone; as input waned, carbonate sedimentation became established.

Facies association 9 (FA 9): This consists mainly of parallel-bedded (*Sa*) and planar cross-bedded (*Sp*) quartz sandstone and wacke, with laminated siltstone and shale (*Fh*) in the Zimmerman Sandstone. Sandstone is mainly very fine to fine grained with minor medium- and coarse-grained sand. Minor facies include low-angle cross-bedded, laminated, and massive sandstone (*Sl*, *Sh* and *Sm*), also massive shale (*Fm*).

Deposition occurred in shoreface (*Sa*) and offshore environments (*Fh*) which were significantly influenced by storms. Texturally inverted and immature sandstone indicates storm reworking of sediments, from shallower shoreface environments, followed by rapid deposition with little opportunity for winnowing. High-energy deposition is also indicated by facies *Sh* and *Sl*. Channels containing facies *Sh* possibly represent storm-rip channels. Coarsening-up sequences of facies *Fh* into *Sh* probably represent the progradation of depositional lobes at the terminus of rip-channels after storms. Fining-up sequences probably represent the return to fair-weather offshore sedimentation after storms. Within offshore environments, thin horizons of facies *Sp* with cross-beds oriented offshore, possibly represent lower energy storm-ebb deposition. Thick horizons of facies *Sp*, with north-south bimodal palaeocurrents and asymmetrical palaeocurrents directed to the south, are shoreface tidal deltas or onshore-directed sandwaves. An interpreted shoaling sequence is present between 54 m and 92 m (Fig. 101). This consists of a basal lag overlain by shoreface sands (*Sl* and *Sa*) followed by a tidal delta or shoreface sandwave complex (*Sp*). It probably represents shoreface or barrier progradation. The remainder of the Zimmerman Sandstone appears to be a random alternation of environments.

Facies association 10 (FA 10): This consists mainly of massive and parallel-bedded quartz sandstone (*Sm* and *Sa*) and laminated siltstone (*Fh*), and occurs in the basal 60 m of the Enga Sandstone. Sandstone is very fine to medium grained and well sorted. Minor facies include: laminated, trough cross-bedded, and planar cross-bedded sandstone (*Sh*, *St*, and *Sp*); massive siltstone (*Fm*) and laminated sandy limestone (*Csh*). Coarsening and thickening-up sequences are common (Fig. 104, section 1000) typically consisting of (in ascending order) facies *Fh*, *Sh*, *Sa*, and *Sm*. Sequences vary in thickness from 2 to 8 m, with the thickest being near the top of FA 10. Tops of sequences (usually facies *Sm*) have a high density of *Skolithos* burrows.

The association was deposited mainly in shoreface environments (*Sa* and *Sm*) with some offshore deposition (*Fh* and *Fm*). Coarsening-up sequences reflect increasing energy and shoaling, from offshore low-energy suspension deposition (*Fh*) to relatively high-energy shoreface deposition (*Sh*, *Sa*, and *Sm*). Beds of densely packed *Skolithos* burrows indicate stillstands. Cross-bedded facies (*Sp* and *St*) occur in thin horizons, and are probably onshore- or longshore-directed dunes. The repetitive occurrence of cycles and their thickening, up the sequence, suggest that they were caused by the overall progradation of the shoreface.

Facies association 11 (FA 11): This consists mainly of parallel-bedded, massive, trough cross-bedded, and planar cross-bedded quartz sandstone (*Sa*, *Sm*, *St*, and *Sp*), with minor low-angle cross-bedded sandstone (*Sl*). The association occurs in the Enga Sandstone at 60–102 m (section 2015) and in the uppermost 55 m (section 2124, Fig. 96). The

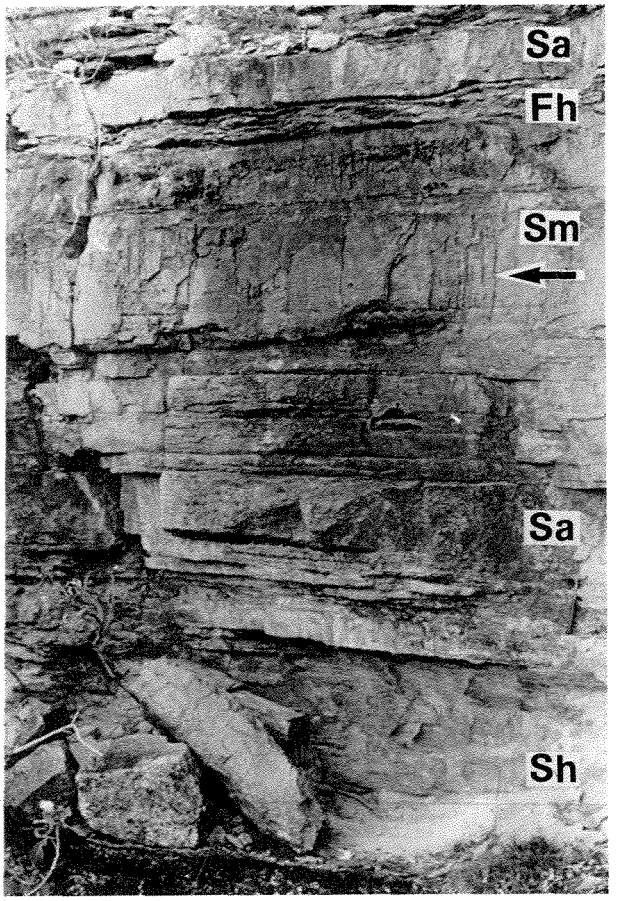

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Figure 104. Coarsening and thickening-up sequence in FA 10. Recessive laminated sandstone (facies *Sh*), passes into parallel-bedded sandstone (Sa), then massive sandstone (*Sm*) with *Skolithos* (arrowed) capping the sequence. This is overlain by bioturbated laminated siltstone (*Fh*) and parallel-bedded sandstone (*Sa*). Enga Sandstone, 1.5 km southeast of the type section.

sandstone is well sorted, fine to medium grained, with scattered granules and rare pebbles. Fining-up sequences, up to 10 m thick, consist of facies *St* overlain by facies *Sa*, with an intensely bioturbated top.

The association was probably deposited in a barrier complex consisting of shoreface environments (*Sa*), tidal channels (*St*) and tidal deltas (*Sp*). Fine-grained, strongly bioturbated facies *Sm* and *Sl* are also probably shoreface deposits, with the extensive bioturbation indicating slow deposition. Fining-up sequences probably result from channel migration, or abandonment, and the establishment of shoreface deposition. Palaeocurrent data for the uppermost channel (5 m thick) show the dominance of flood-tide bed forms directed to the south. Coarse-grained massive facies may be lag deposits, formed at the base of tidal channels, which have otherwise not been preserved. Palaeocurrents to the north and south in facies *Sp* show that both ebb-tibal and flood-tidal sandwaves are preserved. Tidal deltas and channels are dominant in the upper 55 m of the section, whereas shoreface sands are common in the lower section.

DEPOSITIONAL ENVIRONMENT

The mix of siliciclastic-shoreline and carbonate-shelf environments suggests deposition on a clastic-influenced carbonate shelf. In modern settings, such as the Gulf of Mexico and the Atlantic shelf of North America, siliciclastics are deposited shoreward of limestones. In addition, major grain types and facies parallel the shoreline and shelf edge (Reading, 1978). The Langfield Group depositional model (Fig. 105) follows this broad relationship, and the lateral position of facies associations in the model is determined by their vertical (stratigraphic) relationship and the siliciclastic content. The model shows carbonate deposition with major and minor clastic input corresponding to the depositional systems of, respectively, Burt Range Formation–Enga Sandstone and Septimus Limestone–Zimmerman Sandstone.

The siliciclastic belt consisted of either sandstone or siltstone and shale, depending on the proximity of active river input. In the Enga Sandstone, sands introduced by a river were deposited in a barrier complex (FA 11) consisting of tidal channels, tidal deltas and shoreface deposits. These passed seaward into shoreface environments (FA 10), where deposition occurred above fair-weather wave base. Numerous coarsening and thickening-up cycles in FA 10 reflect multiple periods of shoaling, possibly related to the long-shore migration of tidal channels in the barrier, or to the overall shallowing and progradation of the barrier itself.

Seaward of the barrier the carbonate shelf was probably open, as unimpeded wave action builds barriers (Reading, 1978). In the Zimmerman Sandstone, the dominance of siltstone and shale indicates little active clastic input from the hinterland, probably resulting in a narrow sand belt. Sandstones were deposited on a shoreface, and finer clastics were deposited from suspension below fair-weather wave base. Storm periods lowered the wave base, introducing sand from shallower water which was deposited in rip channels and sandwave complexes (FA 9). The generally low-energy depositional regime suggests that most wave energy was dissipated by shoals and barriers, lying further offshore in the carbonate belt.

Most carbonates were deposited in an inner-shelf environment, since grainy textures and lack of mud indicate deposition above fair-weather wave base (Wilson and Jordan, 1983). Local topography and restrictions produced variable textures and depositional environments. In the Burt Range Formation, the seaward part of the shelf contained high-energy shoals capped by lower energy intertidal-supratidal deposits (FA 2). Leeward of the shoals, muddy sediments accumulated in protected areas. The absence of bed forms in the shoals indicates that they formed by vertical aggradation. Winnowed carbonates accumulated away from the shoals on an inner open shelf (FA 3) and became increasingly sandy as the siliciclastic belt was approached (FA 6, FA 8). In the depositional system of the Burt Range Formation–Enga Sandstone the highest energy environment occurred closest to shore, indicating that the carbonate shelf was a gently inclined ramp (Wilson, 1975).

In the Septimus Limestone, high-energy shoals on the inner shelf (FA 4) also contain beach and tidal-channel environments (FA 5). Bedding is common, indicating the shoals were constructed by migrating bed forms. Landward of the shoals, muddy sediments accumulated in protected deeper water, and better sorted barrier sediments accumulated in shallower water (FA 7). Barriers consisted of shoreface and tidal-channel environments. Thick coarsening-up cycles of lagoonal and barrier sediments (in FA 7) represents multiple phases of barrier progradation. Middle-shelf deposits consist of muddy sediment containing no siliciclastics (FA 1). Middle-shelf environments occur in water depths between fair-weather and storm wave base (Wilson and Jordan, 1983) and the depths to each wave base may be a few tens and several tens of metres, respectively. The

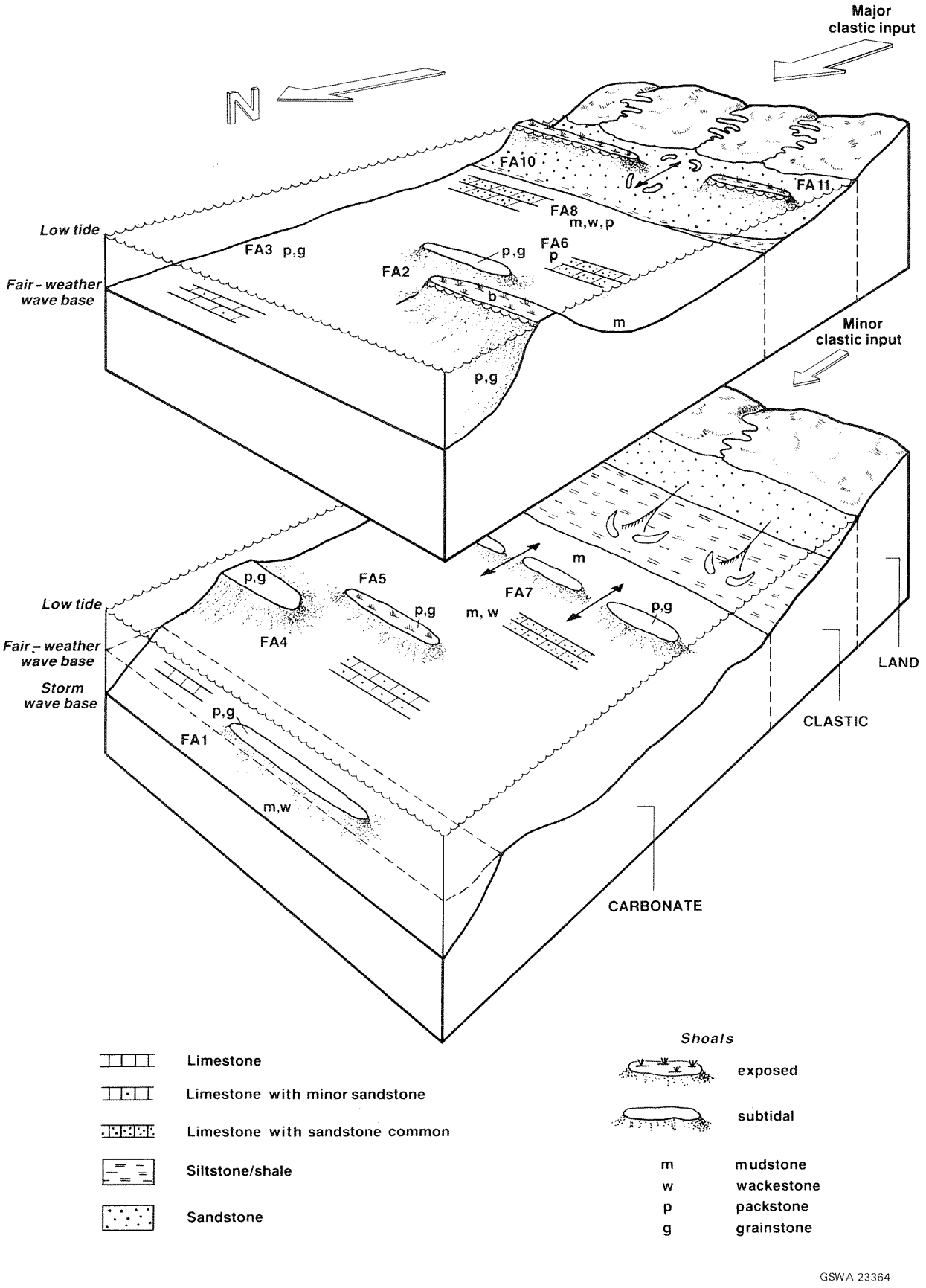


Figure 105. Depositional model for the Langfield Group showing settings of facies associations.

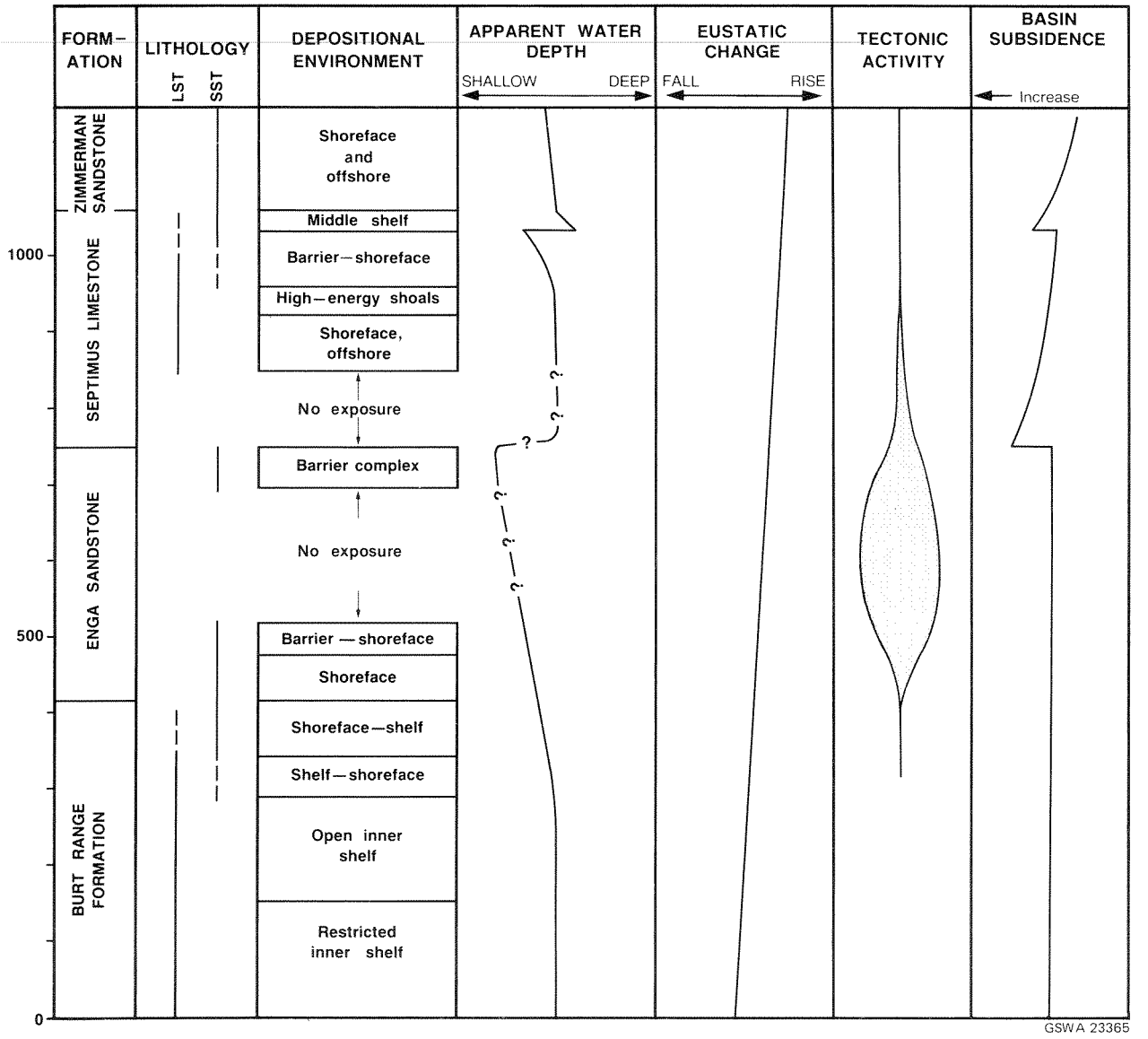


Figure 106. Eustatic and tectonic controls on the depositional evolution of the Langfield Group.

coarsening-up cycle and grainy sediments at the top of FA 1 indicate shallowing due either to vertical aggradation, or to lateral progradation of inner-shelf environments. In the depositional system of the Septimus Limestone–Zimmerman Sandstone, highest energy environments occurred away from the shore, indicating that the shelf had a relatively steep outer margin or a 'drop-off' type of profile (Wilson and Jordan, 1983).

With regard to depositional history and tectonics, the Langfield Group consists of two carbonate-to-clastic sequences, representing progradation of shoreline clastics over shelf carbonates. Cycles of this magnitude reflect basin-wide influences such as tectonic uplift, basin subsidence, and eustatic changes. Carbonate-grain production is probably also important in producing cycles in the carbonate sequences. During the Tournaisian the sea level was rising relatively slowly (Vail and others, 1977) and if no other factors operated, the basin should have slowly deepened. Assuming the eustatic rise was smooth, the contrary and abrupt changes in apparent water depth (Fig. 106) are due to local influences.

Coarse siliciclastics in the upper part of the lower cycle suggest that basin shallowing and progradation (Fig. 106) were caused by tectonic uplift of the hinterland. The maintenance of a stable apparent sea level, earlier in the cycle, indicates that carbonate-grain production kept pace with basin subsidence. The gradational vertical contact between Burt Range Formation and Enga Sandstone indicates that carbonate deposition continued with sand input. Relative deepening of the basin at the top of the cycle reflects a combi-

nation of decreased clastic input (and tectonism) and possibly an increase in basin subsidence.

The dominance of fine siliciclastics in the upper part of the second cycle, suggests that uplift ceased and the hinterland had a low relief. Hence, progradation was probably caused by a lower rate of basin subsidence. Basin shallowing in the upper part of the Septimus Limestone indicates that carbonate-grain production exceeded basin subsidence. Basin deepening (to middle-shelf environments) possibly reflects either continued basin subsidence, with decreased carbonate-grain production, or an increase in the subsidence rate. Major clastic influx, marked by the boundary of Septimus Limestone–Zimmerman Sandstone, effectively stopped carbonate production.

BONAPARTE FORMATION

Definition: The Bonaparte Formation ("Bonaparte Beds", Veevers and Roberts, 1968; amended by Beere and Mory, 1986) is a subsurface unit of shale, siltstone, sandstone, and minor sandy limestone. Veevers and Roberts (1968) designated the type section in Bonaparte 1 between 497 m and 3210 m. However, a dip-meter angular unconformity at 2280 m (Fig. 108) separates the Bonaparte Formation (below) from the Milligans Formation (above). The unconformity occurs within a shale sequence and coincides with a marked change on the gamma-ray logs and a lesser change on the resistivity logs (Le Blanc, 1964).

Lithology: The type section consists of shale and siltstone, with interbedded sandstone and minor sandy limestone. Sandstone is very fine to fine grained and may be calcareous. Compared to the Milligans Formation, the unit is sandier, and it contains chlorite, calcite, and dolomite (Loughnan, *in* Veevers and Roberts, 1968, p. 116). The type lithology persists in other wells. In Weaber 1 the sandstones are well sorted and dolomitic (Garside, 1982). In Keep River 1 the unit consists of two fining-up sequences 125 m and 224 m thick (at 3222–3 446 m and 3446–3571 m). It consists of a basal sandstone and/or sandy limestone overlain by calcareous siltstone, siltstone, and silty shale which Caye (1969) identified as Enga Sandstone and Burt Range Formation.

Stratigraphic relationships: The Bonaparte Formation is unconformably overlain by the Milligans Formation and is probably laterally equivalent to the Langfield and Ningbing Groups, and possibly equivalent to the Cockatoo Group. The unconformity in Bonaparte 1 amounts to several degrees, with the Milligans Formation dipping 2–3° to the north, and the Bonaparte Formation dipping 4–6° to the east and east-southeast (Caye, 1969). In Kulshill 1 the Visean Milligans Formation unconformably overlies the Upper Devonian Bonaparte Formation. In Keep River 1 and Weaber 1 the Bonaparte Formation occurs between the Enga Sandstone and Ningbing Group, indicating correlation with the Burt Range Formation of the Langfield Group.

Distribution and thickness: The Bonaparte Formation occurs in the onshore part of the basin in Bonaparte 1, Keep River 1, Weaber 1, Kulshill 1, and probably Bonaparte 2. In Bonaparte 2 an undated sandy section, between 1750 m and 2136 m (containing rare sandy limestone) is similar to the Bonaparte Formation. The type section is the thickest known at 930 m (at 2280–3210 m) but the base was not reached. The thinnest complete sequence is 279 m in Weaber 1 (1388–1667 m) and in Kulshill 1 the formation is 633 m thick (3762–4395 m).

Fossils and age: Fossils in the type section occur only between 2280 m and 2829 m, and include bivalves, conchostracans, trilobites, ?goniatites, a ?clymeniid and *Leptophloem australe* (Le Blanc, 1964). Crinoids, ostracods, brachiopods, bryozoans, and stylioline fragments occur in Keep River 1 (Caye, 1969). Plants, foraminifers, echinoids, algae, molluscs, ostracods and conodonts occur in Kulshill 1 (Duchemin and Creevey, 1966).

In Bonaparte 1, bivalves indicate a Late Devonian age (Le Blanc, 1964) and in Kulshill 1 the unit is of Middle to Late Devonian age (Duchemin and Creevey, 1966; Veevers and Roberts, 1968). A Tournaisian age is indicated in both Keep River 1 (Caye, 1969) and Weaber 1 (Garside, 1983).

Depositional environments: The Bonaparte Formation was probably deposited in a quiet-water marine shelf or deep basin of unknown water depth which was laterally equivalent to Frasnian continental and shallow-marine environments (Cockatoo Group), Famennian reef-complex (Ningbing Group) and Tournaisian shelf environments (Langfield Group). A precise correlation is not possible, but if sandstone deposition in the basin was simultaneous with shelf and reef carbonate deposition, then clastic by-pass channels from shoreward sources must have existed. In the marine environment, sandstone transportation was probably by turbidity currents, and thick sandy sequences in Keep River 1 may represent submarine fans with the fining-up sequences due to fan abandonment.

CHAPTER 6

Latest Tournaisian to Westphalian of the Bonaparte Basin

INTRODUCTION

Latest Tournaisian to Westphalian sediments of the Bonaparte Basin are assigned to the Weaber Group. Reeves (1948) and Traves (1955) made the first observations on this unit. These authors were only able to examine a small part of the group, which they considered to be Permian. Three of the formations which Traves (1955) included within the group are now assigned to underlying units (Veevers and Roberts, 1968).

WEABER GROUP

The Weaber Group (Traves, 1955), consists of Milligans Formation, Waggon Creek Formation, Utting Calcarenite, Burvill Formation, Point Spring Sandstone, and Tanmurra Formation. The Waggon Creek Formation and Utting Calcarenite are lenticular units between the Milligans and Burvill Formations. The group overlies all older units with angular unconformity, and is overlain by the Keep Inlet Formation, unconformably in onshore areas, or conformably in offshore areas. The group occurs in both the Burt Range and Carlton Shelves, also in the Petrel Sub-basin.

The group consists mainly of shale and sandstone, with minor siltstone, conglomerate, and limestone. Coarser clastics and limestone outcrop mainly in Weaber Range, east and south of Ningbing Range (Fig. 107), and at Spirit Hill in the Northern Territory. Shales outcrop poorly and are mainly known from drill-hole intersections. About 600–700 m of sediment occur around Weaber Range, consisting equally of shale and overlying sandstone and conglomerate. To the north, sandstones maintain a similar thickness but shales thicken considerably so that the group totals 2400 m in Keep River 1. The group is of late Tournaisian to possibly Westphalian age.

MILLIGANS FORMATION

Definition: The Milligans Formation consists of shale and minor siltstone at the base of the Weaber Group. "Milligans Beds", was used by Utting (1958) for Carboniferous shales which underlie the Keep River plain, and by Hare and Thomas (1961) for Visean shale and siltstone in Spirit Hill 1. Late Devonian and Early Carboniferous shale and siltstone, in Bonaparte 1 and 2 and Kulshill 1 and 2, were also included in the "Milligans Beds" by some workers (Le Blanc, 1964, 1965; Duchemin and Creevey, 1966; Creevey, 1966). Veevers and Roberts (1968) designated the type section at 44–155 m in Milligans 1 stratigraphic hole, at the southeast corner of Milligans Hills. They restricted the unit to the Carlton and Burt Range Shelves so that intersections in the oil wells were referred to the Bonaparte Formation. Here, we concur with earlier usage and extend the unit to the Petrel Sub-basin so that it includes Tournaisian to Visean shale, assigned to the Bonaparte Formation by Veevers and Roberts (1968).

Lithology: The type section consists of grey to black silty shale, which is locally calcareous, gypsiferous, or pyritic. It contains microfossils as well as shell fragments, crinoids, and bryozoans (Veevers and Roberts, 1968). In deep exploration wells, the Milligans Formation consists mainly of shale, with minor silty shale, and some interbedded sandstone, siltstone, limestone, pebbly sandstone, and conglomerate. In Ningbing 1 the sequence contains abundant siltstone (Garside, 1983). In Keep River 1, a sequence (700 m thick) of sandstone, siltstone, and minor limestone within the Milligans Formation is placed in the Waggon Creek Formation (Fig. 108). Outcrops of the Milligans Formation 3 km north-northeast of Ningbing homestead (Fig. 107) consist of partly calcareous shale and minor flaggy siltstone, fine sandstone, and limestone. Limestones are ferruginized packstone and grainstone, with crinoids, brachiopods, green algae, intraclasts, and peloids.

Stratigraphic relationships: The Milligans Formation unconformably overlies older units, and conformably underlies other Weaber Group sediments. The lower contact is not exposed but in the Carlton and Burt Range Shelves the Milligans Formation overlaps the Cockatoo, Ningbing, and

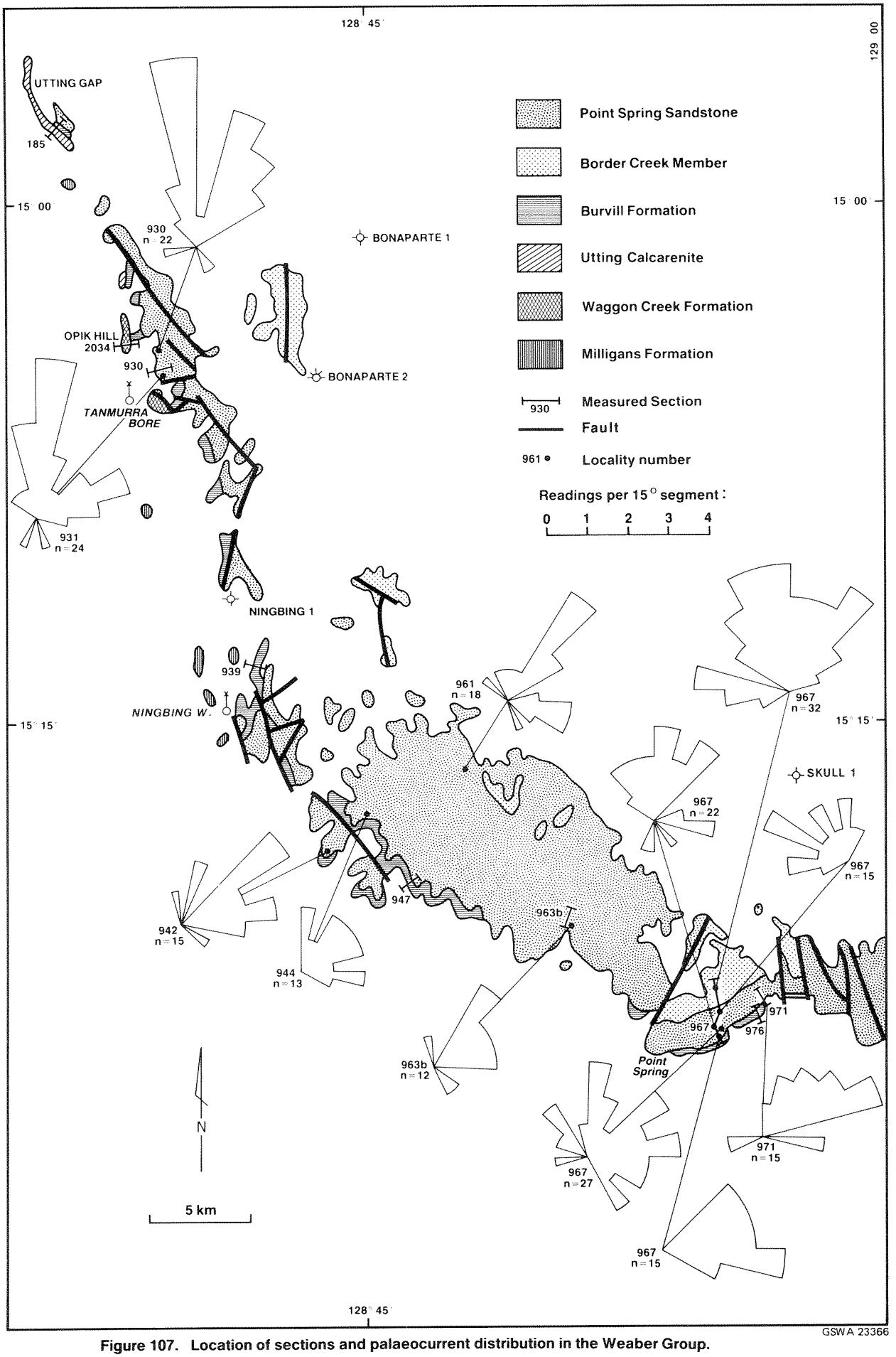


Figure 107. Location of sections and palaeocurrent distribution in the Weaber Group.

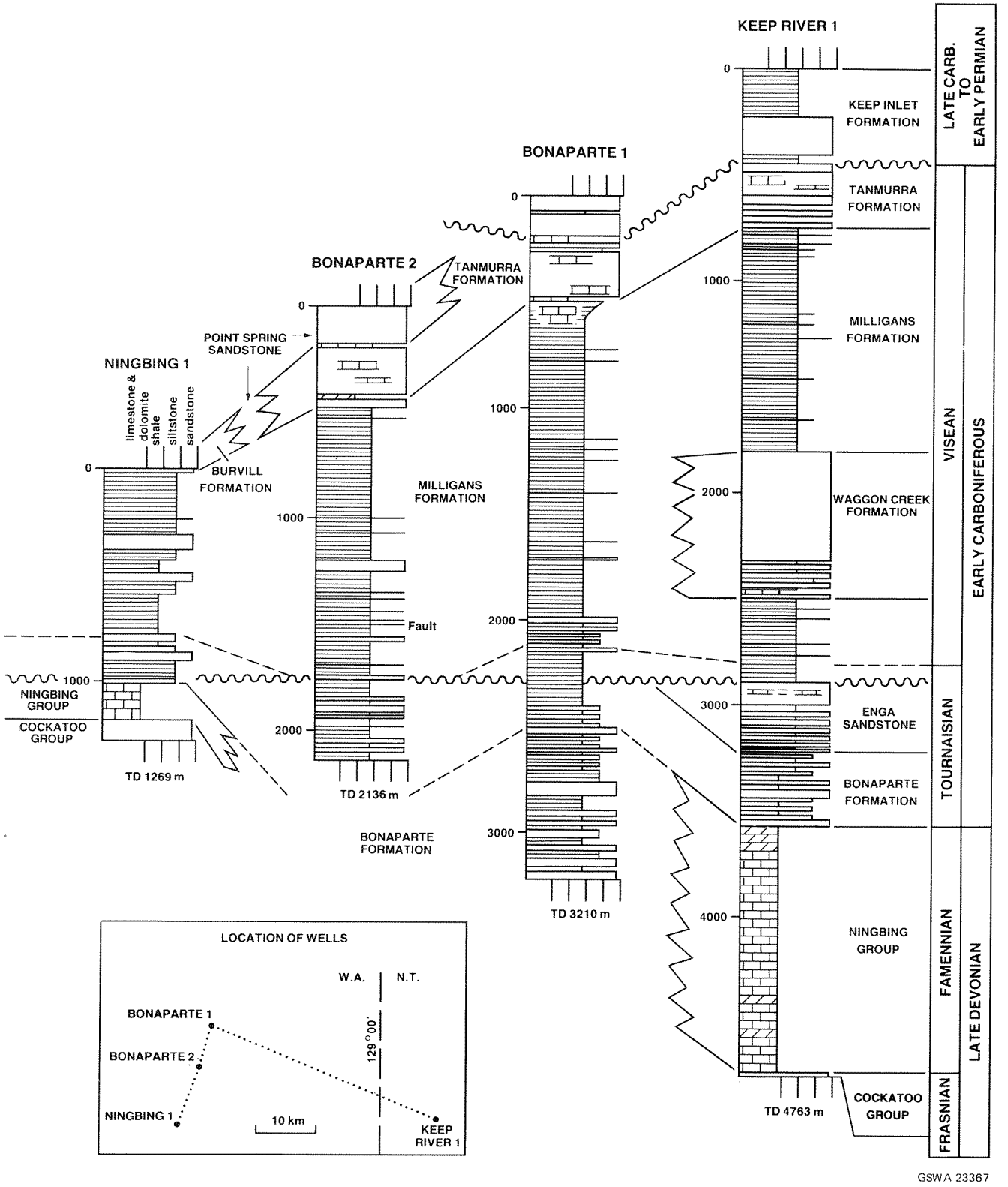


Figure 108. Correlation of stratigraphy in deep oil-exploration wells (based on data available to 1984). Key to symbols in Figure 3.

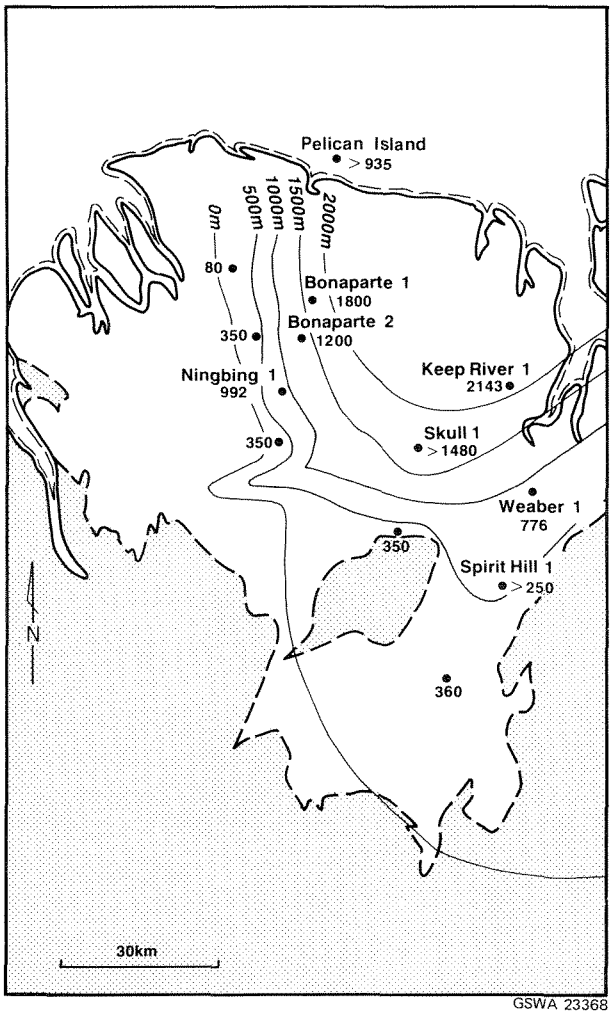


Figure 109. Milligans Formation isopachs.

Langfield Groups (Plate 1) suggesting an angular relationship. In Bonaparte 1, an angular unconformity at 2280 m (Le Blanc, 1964) separates the Milligans Formation and the underlying Bonaparte Formation (Fig. 108). The Milligans Formation conformably underlies the Burvill Formation. Drill-hole data, at Milligans Hills and east of Ningbing Range, show that the units are lithologically gradational. However, Veevers and Roberts believed a hiatus existed on the basis of an Early Visean age for Milligans Formation at Milligans Hills together with a Late Visean age for Burvill Formation at Weaber Range. The Utting Calcarenite and Waggon Creek Formation, locally, lie between the Milligans and Burvill Formations.

In the Spirit Hill area, the Milligans Formation is overlain by the Keep Inlet Formation, with a probable angular unconformity.

Distribution and thickness: The Milligans Formation occurs beneath coarser sediments of the Weaber Group in a belt extending from Utting Gap, southwards along the east side of Ningbing Range, eastwards between the Weaber and Pincombe Ranges, and southwards to Milligans Hills. Outcrops are known only around Ningbing Well. The unit occurs in all deep exploration wells, basinwards of this belt.

The unit is thinnest around its area of subcrop (300–350 m). It rapidly thickens towards the centre of the Petrel Sub-basin (Fig. 109), with the maximum rate occurring east from Ningbing Range.

It is absent or very thin (28 m) beneath Utting Calcarenite at Utting Gap, while 16 km to the east it thickens to about 1800 m in Bonaparte 1. Full stratigraphic thicknesses have also been intersected in Ningbing 1 (992 m), Weaber 1 (776 m), and Keep River 1 (2142 m). In Bonaparte 2, about 1200 m is present although the sequence is complicated by faulting.

Fossils and age: The Milligans Formation contains abundant and diverse fossils including ostracods, trilobites, foraminifers, conodonts, bivalves, gastropods, crinoids, brachiopods, echinoids, bryozoans, corals, holothurians, fish scales, scolecodonts, green algae, tracheid plant fragments, and spores.

In Bonaparte 1, foraminifers indicate that the unit ranges from latest Tournaisian (Tn3c) near the base to late Visean (V3b-c) near the top (Mamet and Belford, 1968; Veevers and Roberts, 1968).

WAGGON CREEK FORMATION

Definition: The Waggon Creek Formation ("Waggon Creek Breccia" of Veevers and Roberts, 1968, amended by Beere, 1984) consists of pebbly sandstone, conglomerate, sandstone, and shale. The type section is near the head of Waggon Creek on the northern side of Pretlove Hills, about 13 km north-northeast of Carlton Hill (base 15°22′40″S, 128°34′30″E; top 15°22′40″S, 128°34′20″E). Beere (1984) designated a reference section, 2 km west of the type section, to show the upper part of the formation.

Lithology: The type area consists of a lower unit of pebbly sandstone, conglomerate, and minor sandstone, followed by an upper unit of sandstone and shale (Beere, 1984). There is little outcrop *in situ* and coarser lithologies occur in displaced blocks, indicating that interbedded shale has been weathered out.

Pebbly sandstone and sandstone range from fine to coarse grained, and are well to poorly sorted. Pebbles up to 12 cm in diameter are mainly quartzite, with minor shale and rare dolomite.

Conglomerate is clast- and matrix-supported. Clasts are mainly subangular to subrounded quartzite and shale, up to 20 cm in diameter, with locally abundant dolomite up to 70 cm in diameter. Exceptionally, dolomite blocks reach 15 m in diameter. The dolomite includes stromatolitic, oolitic, laminated, massive, and sandy types, and rare cobbles of *Syringopora*. Many clasts were probably derived from the Cambrian Skewthorpe Formation and the Devonian Hargreaves Formation (Beere, 1984). Beds vary from 5 cm to 1.5 m thick, with the thinner beds being composed of finer lithologies. Most beds are massive, but normal grading and rare inverse grading are present. The sandstone also contains minor lamination, parallel bedding, ripples, and rare cross-bedding; it may also have flute- and tool-marked soles. Shale is poorly exposed 3 km west of the type section.

A well-exposed sequence at Opik Hill is similar to the lower unit in the Waggon Creek area, consisting mainly of pebbly sandstone, with minor conglomerate, sandstone, and shale (Fig. 110, section 2034). Conglomerate and pebbly sandstone are sand-supported, or rarely, clast-supported. Clasts consist of quartzite pebbles (up to 6 cm in diameter) and subangular to subrounded tabular shale pebbles, cobbles, and rare boulders (up to 1 m in diameter). Beds up to 6 m thick are massive or normally graded, or rarely, inversely graded. Sandstone is medium to coarse grained and moderate to poorly sorted; it also contains minor quartzite and shale pebbles. Beds are up to 2.5 m thick and contain lamination, parallel bedding, and rare cross-bedding. Massive and laminated shale occurs in beds up to 2 m thick and may contain thin, normally graded sandstone beds.

At Tanmurra Bore, 3 km south of Opik Hill, a sequence of flaggy sandstone, shale, and rare conglomerate, is similar to the upper unit in the Waggon Creek area. Sandstone is medium to fine grained, moderately to well sorted, contains scattered shale intraclasts, and is thin to medium bedded. Sole marks are common and include flutes, brush marks, and load casts. Beds are massive or laminated, and may have rippled or parting-lineated tops. Conglomerate is matrix- or clast-supported and massive or parallel bedded. Clasts include quartzite pebbles and tabular shale boulders up to 1 m in diameter. Conglomerate beds 2.5 km east of Tanmurra Bore have been slump folded.

The Waggon Creek Formation is exposed in the northeastern part of Spirit Hill in the Northern Territory where the sequence is similar to that at Tanmurra Bore.

Stratigraphic relationships: The Waggon Creek Formation is a lenticular and probably diachronous unit within the Milligans Formation. In the area of Opik Hill–Tanmurra Bore the unit lies conformably between the Milligans Formation, below, and the Burvill Formation above. To the north, at Utting Gap, this stratigraphic position is occupied by the Utting Calcarenite, while to the south the Burvill Formation directly overlies Milligans Formation. At Spirit Hill, the Waggon Creek Formation conformably overlies the Milligans Formation and is overlain with angular unconformity by the Keep Inlet Formation.

The stratigraphic relationships with Milligans Formation are poorly known in the type area. The Waggon Creek Formation dips to the north and overlies the Hargreaves Formation (Cockatoo Group) with angular unconformity, and the top is not exposed (Beere, 1984). Milligans Formation occurs 4 km to the north. If the Milligans and Waggon Creek Formations are conformable, then Milligans Formation must either overlie, or at least be laterally equivalent to, the Waggon Creek Formation.

Thick sand bodies, within Milligans Formation, in Keep River 1 (1810–2500 m) and Bonaparte 2 (1197–1246 m) are probably Waggon Creek Formation.

Distribution and thickness: The Waggon Creek Formation forms outcrops only in the areas of Waggon Creek, Opik Hill, Tanmurra Bore, and Spirit Hill. Restricted lateral distributions suggest the unit is lenticular. In the northeast Pretlove Hills (Plate 1) a thin sequence of sandstone, unconformably overlying the Hargreaves Formation, is also regarded as Waggon Creek Formation. The unit is also present in Keep River 1 and Bonaparte 2.

The type section is 86 m thick, the reference section, 120 m thick, is the thickest known outcropping section. The thickest section (690 m) is in Keep River 1.

Fossils and age: Veevers and Roberts (1966) record brachiopods, bivalves, gastropods, corals, and crinoids in the Waggon Creek Formation in the type area. Trace fossils occur within shales and on the soles of some sandstone beds. The shale also contains fish plates and wood fragments (Beere,1984). In the type area, boulders of *Syringopora*, trilobitic sandstone, and laminated and stromatolitic dolomite, were probably derived from older rocks.

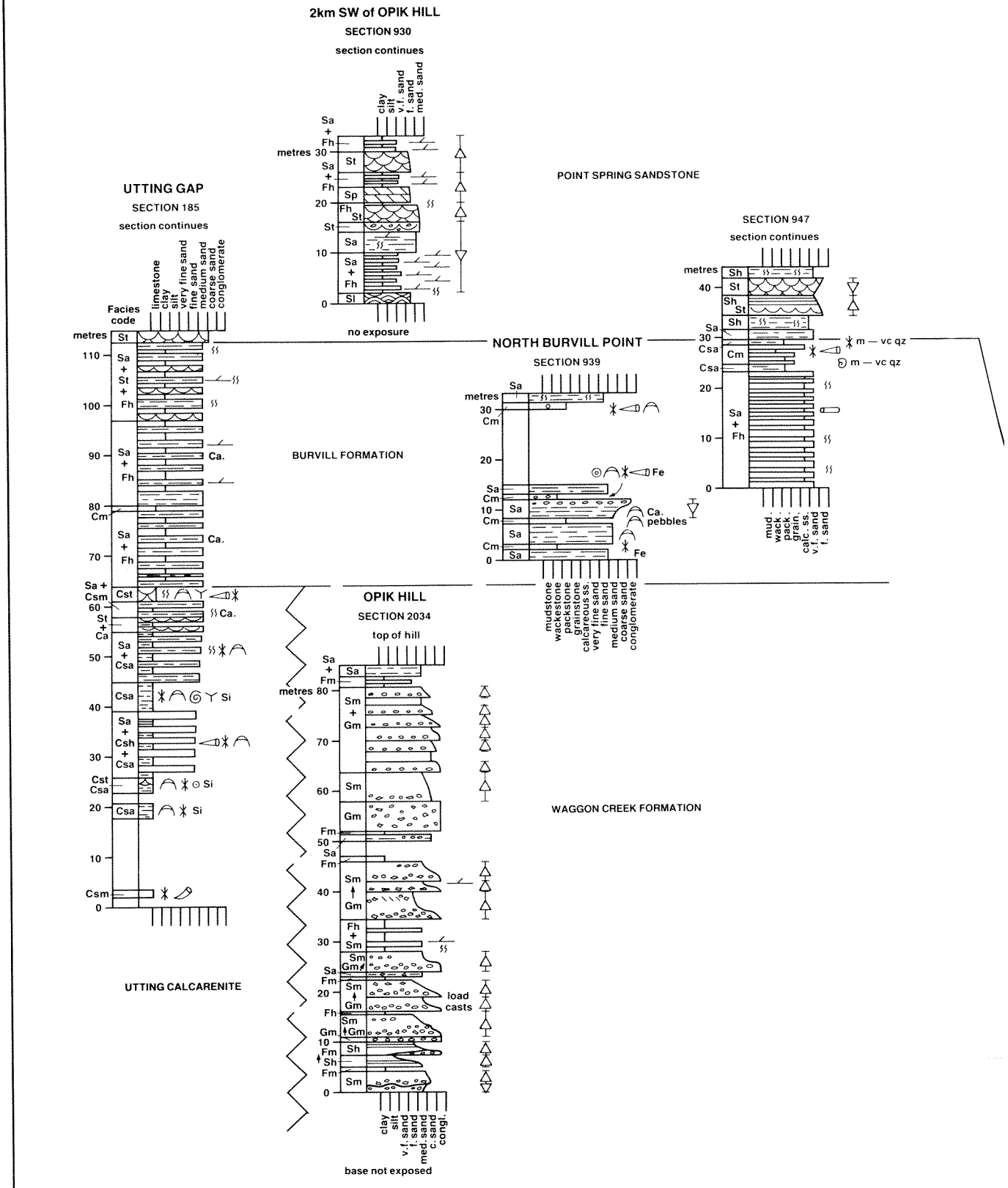
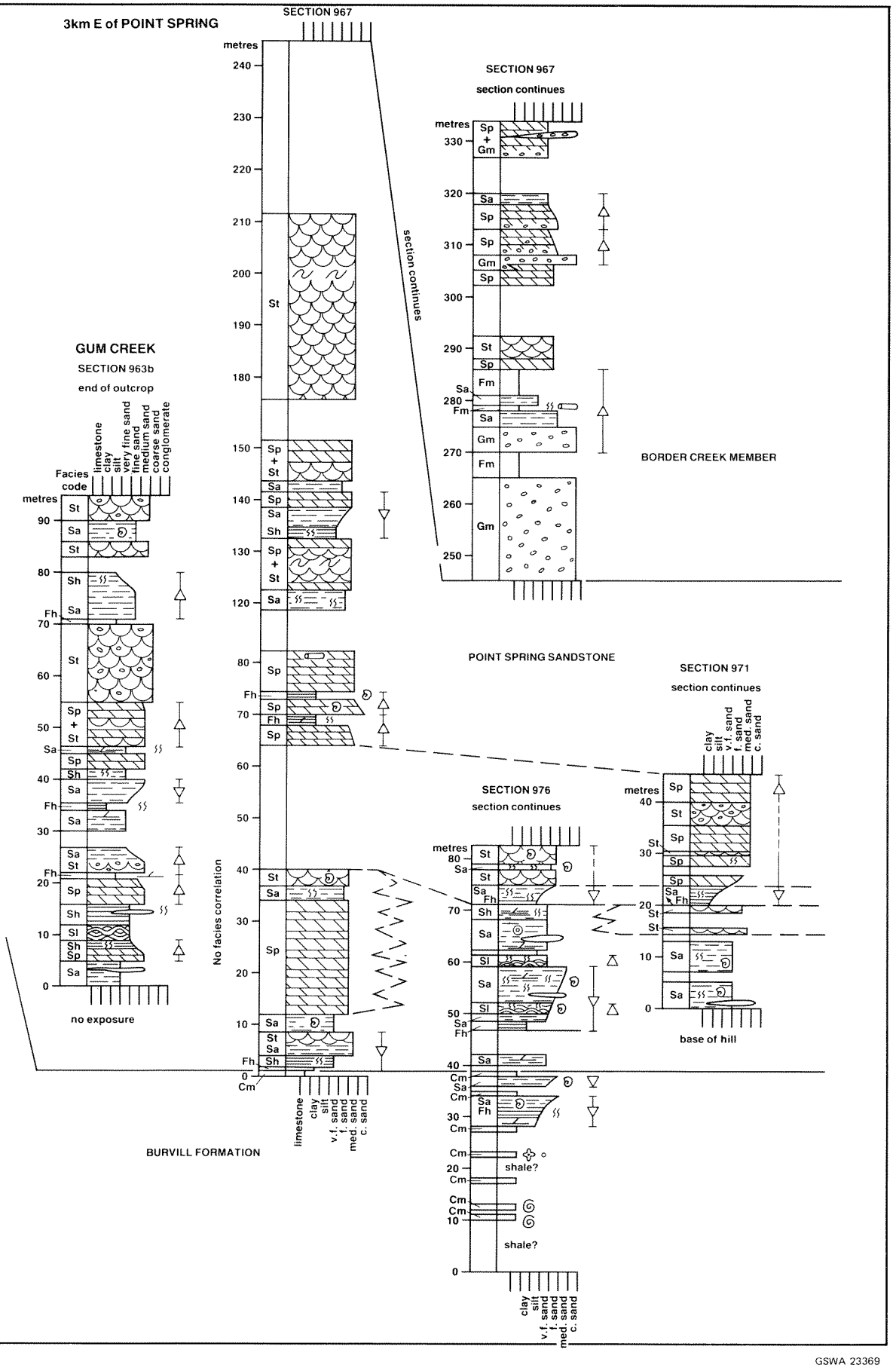


Figure 110. Measured sections in the Weaber Group. Section locations shown in Figure 107, facies codes in Tables 1, 8 and 11, key to symbols in Figure 3.


3km E of POINT SPRING
SECTION 967
metres
240
230
220
210
200
190
180
150
140
130
120
80
70
60
50
40
30
20
10
0
St
Sp + St
Sa
Sp
Sh
Fh
Cm
section continues
SECTION 967
section continues
metres
330
320
310
300
290
280
270
260
250
Sp + Gm
Sa
Sp
Gm
St
Fm
BORDER CREEK MEMBER
GUM CREEK
SECTION 963b
end of outcrop
Facies code
limestone
clay
silt
very fine sand
fine sand
medium sand
coarse sand
conglomerate
metres
90
80
70
60
50
40
30
20
10
0
Sl
no exposure
POINT SPRING SANDSTONE
No facies correlation
SECTION 971
section continues
clay
silt
v.f. sand
f. sand
med. sand
c. sand
SECTION 976
section continues
shale?
base of hill
BURVILL FORMATION

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The Waggon Creek Formation is probably a diachronous unit of Visean age. A restricted brachiopod fauna collected from the type section indicates a late Visean to possibly Namurian age (Roberts, 1971). Similar rocks a few kilometres to the east yielded mid-Tournaisian fossils (Veevers and Roberts, 1968; Roberts 1971), which Beere (1984) suggested were possibly reworked. In the vicinity of Opik Hill–Utting Gap, stratigraphic evidence suggests that the Waggon Creek Formation is about the same age as the early Late Visean Utting Calcarenite, slightly older than suggested by Veevers and Roberts (1968) and Roberts (1971). The occurrence of Waggon Creek Formation being stratigraphically low in the Late Tournaisian to Visean Milligans Formation, in Keep River 1 and Bonaparte 2, suggests that the unit may be older than late Visean.

UTTING CALCARENITE

*Definition:*The Utting Calcarenite (Veevers and Roberts, 1968) is a unit of sandy limestone, calcareous sandstone, and minor sandstone. The type section is in Utting Gap, about 12 km north-northwest of Opik Hill (base 14°58′10″S, 128°35′40″E; top 14°58′10″S 128°35′50″E).

Lithology: The unit consists of sandy limestone, calcareous sandstone, and sandstone (Fig. 110, section 185). Limestone consists of wackestone and packstone, with fragmented and locally silicified fossils together with fine- to medium-grained quartz. It is similar to limestone in the Burvill Formation. Sandstone is fine to medium grained and moderate to poorly sorted. Thin to medium parallel beds (< 0.3 m) are dominant with minor thin to medium trough cross-bedding. Sandy limestone may also be massive or laminated.

Stratigraphic relationships: The Utting Calcarenite is a lenticular unit lying conformably between the Milligans Formation, below, and the Burvill Formation above. In the type section, the Utting Calcarenite is probably faulted against the Ningbing Group, because dips in the former steepen towards the contact. Drilling shows a sharp contact with Milligans Formation. Despite the similar stratigraphic positions of the Waggon Creek Formation and Utting Calcarenite, a lateral transition has not been observed and the Milligans Formation is inferred to separate them. Lithostratigraphically, the Utting Calcarenite probably correlates with a peloidal sandy calcarenite, 20 m thick, at the base of the Tanmurra Formation in Bonaparte 1.

Distribution and thickness: The Utting Calcarenite outcrops at Utting Gap and in a narrow belt extending 4.5 km to the north-northwest; it also occurs as isolated hills located up to 8 km to the south. The absence of the unit immediately east of Utting Gap (Plate 3, section BB′) may be due either to faulting or, more likely, a very rapid facies change.

The type section, 64 m thick, is the thickest known section; other drill holes around Utting Gap record only 36 m. Veevers and Roberts (1968) estimated more than 122 m of section, 1 km south of the Utting Gap, although this probably included some Milligans Formation (Plate 1).

Fossils and age: The Utting Calcarenite contains a rich fauna of brachiopods, tabulate and rugose corals, trilobites, foraminifers, ostracods, conodonts, and sharks (Veevers and Roberts, 1968). Crinoids, gastropods, bryozoans, bivalves, and trace fossils are also present.

An early Visean age is indicated by brachiopods (Thomas, 1965) and conodonts (Druce, 1969), although foraminifers indicate an early Late Visean (V3a-b) age (Mamet and Belford, 1968), consistent with its stratigraphic position.

BURVILL FORMATION

Definition: The Burvill Formation ("Burvill Beds", Veevers and Roberts, 1968) is a unit of sandstone and minor siltstone, shale, calcareous sandstone, and sandy limestone. The type section is at Burvill Point, 1.5 km east of Ningbing homestead (base 15°15′00″S, 128°41′20″E; top 15°14′50″S, 128°41′00″E).

Lithology: Most sandstone is very fine to fine grained, well to very well sorted, bioturbated, and contains body fossils. Medium- to coarse-grained, moderate- to well-sorted sandstone, with scattered pebbles, is locally common. Thin parallel bedding is dominant and the outcrop consists mainly of flaggy rubble, suggesting interbedding with shale. Ripples, low-angle cross-bedding, lamination, and completely bioturbated beds are also present. Sandy limestone and calcareous sandstone are commonly ferruginized, occur in isolated beds up to 5 m thick, and are massive or thin to medium parallel bedded. Subangular to angular, medium- to coarse-grained, quartz grains commonly are disseminated in a calcareous matrix, with rare scattered granules and small pebbles. Sandy limestone includes wackestone, packstone, and minor mudstone; fossils are common. Calcareous sandstone contains rare corals. Siltstone outcrops

poorly, and is laminated or rippled, and commonly bioturbated. Shale intersected in drill holes around Burvill Point is sandy, silty, pyritic, and micaceous.

Stratigraphic relationships: The Burvill Formation lies conformably between the Milligans Formation and the Point Spring Sandstone. Locally, it conformably overlies the Utting Calcarenite and the Waggon Creek Formation.

The lower contact with the Milligans Formation is lithologically gradational in Milligans 1 stratigraphic hole (Veevers and Roberts, 1968) and in drill holes around the type section at Burvill Point. The contact with the Utting Calcarenite is exposed at Utting Gap (Fig. 110). The contact with the Waggon Creek Formation is probably conformable although it is not exposed at Opik Hill and is faulted in the Tanmurra Bore area.

The Point Spring Sandstone is lithologically gradational with the Burvill Formation. East of Point Spring the contact is arbitrarily taken at either the last sandy limestone or first cross-bedded sandstone.

Distribution and thickness: The Burvill Formation outcrops discontinuously in a belt from Utting Gap, southwards, through Burvill Point, and along the southern front of Weaber Range. An isolated outcrop occurs at Milligans Hills. It occurs in shallow drill holes between Utting Gap and Burvill Point, and at Milligans Hills, but has not been recognized in deep oil-exploration bores.

The type section is 49 m thick and the thickest known section (85 m) occurs in eastern Weaber Range (Veevers and Roberts, 1968). These are minimum thicknesses, as the base is not exposed.

Fossils and age: The Burvill Formation contains a diverse assemblage including brachiopods, gastropods, corals, crinoids, plants, scyphozoans, ostracods (Thomas, 1962), conodonts (Veevers and Roberts, 1968), trace fossils, and green algae. Diverse horizontal and vertical burrows (including those of *Diplocraterion* and *Rhizocorallium,*) together with plant fossils, occur mainly in the sandstones. Solitary and compound corals, green algae, calcispheres, oncolites, and pellets occur mainly in sandy limestones.

A late Visean to Namurian age is indicated by brachiopods (Roberts, 1971) and conodonts from Weaber Range (Druce, 1969). Foraminifers indicate a late Visean age (Mamet and Belford, 1968). The Burvill Formation may be a diachronous unit, younging to the north. The section at Weaber Range is probably a time equivalent to the Utting Calcarenite at Utting Gap (Cockbain, 1985) and to limestone at the base of the Tanmurra Formation in Bonaparte 1 (Veevers and Roberts, 1968).

POINT SPRING SANDSTONE

Definition: The Point Spring Sandstone (Traves, 1949) consists of sandstone and pebbly sandstone, with minor conglomerate and siltstone. Traves (1955) defined the unit as "sandstones and other sediments which crop out in Weaber Range", and using Reeves' (1949) sections in eastern Weaber Range, he included limestone at the base and conglomerate at the top. Veevers and Roberts (1968) designated a type section 6 km east-northeast of Point Spring (base 15°23′20″S, 128°56′10″E; top 15°22′10″S, 128°56′00″E) and included the upper and lower lithologies in the "Burvill Beds" and "Border Creek Formation", respectively. As a result of our mapping, Cockbain (1985) considered the "Border Creek Formation" to be a member of the Point Spring Sandstone.

The Border Creek Member (Border Creek Formation, in part, of Utting, 1958, and Veevers and Roberts, 1968) is a sequence of conglomerate, siltstone, pebbly quartz sandstone and minor quartz sandstone. The type section is 4.2 km northeast of Point Spring from 15°23′30″S, 128°55′00″E (base) to 15°22′00″S, 128°54′40″E (top). The Border Creek Member is here assigned member status within the Point Spring Sandstone because the conglomerate, which distinguishes this unit, is lenticular and probably diachronous. In the type area the first conglomerate appears 240 m above the base of the Point Spring Sandstone (Fig. 110) whereas 2.5 km to the east this conglomerate lies only 140 m above the base of the formation and is demonstrably lenticular along strike. Furthermore the member is overlain by sandstones indistinguishable from those below this unit.

Lithology: Sandstone and pebbly sandstone are fine to medium grained, moderate to well sorted, mature to supermature quartz arenite. Very fine- and coarse-grained sandstone is also present, and scattered small pebbles are of quartz and rare siltstone. Around Point Spring the unit generally coarsens upwards, in that fine sandstone is common in lower parts of the formation, and the size and amount of pebbles increase up-section. Sandstone is medium to thick trough or planar cross-bedded, thin to medium parallel bedded, and laminated. Minor structures include ripples, low-angle cross-bedding, contortion, and massive bedding. Body fossils and diverse bioturbation structures are common in parallel-bedded sandstone,

but rare in cross-bedded sandstone. Siltstone, grading to very fine sandstone, is laminated, massive, or (more rarely) rippled. Locally it is ferruginized and silicified, and very rarely contains body fossils.

The Border Creek Member contains thick beds of conglomerate and siltstone. The conglomerate occurs generally as float, and clasts consist of pebbles, cobbles, and rare boulders (up to 0.7 m) of rounded to well-rounded quartzite and lesser siltstone. Outcrops *in situ* show massive bedding and, rarely, trough cross-bedding. The sandstone is texturally similar to that in the Point Spring Sandstone, but planar cross-bedding is dominant.

Stratigraphic relationships: The Point Spring Sandstone conformably overlies the Tanmurra and Burvill Formations, and is possibly unconformably overlain by the Keep Inlet Formation. Laterally it is equivalent, in part, to the Tanmurra Formation. Lithologically the unit is gradational with the Burvill Formation, and the boundary in outcrop is placed at the last limestone bed or (where there is no limestone) the first cross-bedded sandstone. In Bonaparte 2 the Point Spring Sandstone (Border Creek Formation of Veevers and Roberts, 1968) conformably overlies the Tanmurra Formation.

Previously unnamed, very fine- to very coarse-grained, quartz sandstone and minor shale in Pelican Island 1 (ARCO Australia Ltd, 1972; Cockbain, 1985), correlate on a lithostratigraphic basis with the Point Spring Sandstone. The Tanmurra Formation grades up into this sandstone. Together the two units form a coarsening-upward sequence which becomes less calcareous upwards, similar to the sequence in Bonaparte 2.

The contact with Keep Inlet Formation is poorly known. In Pelican Island 1 the Keep Inlet Formation overlies the Point Spring Sandstone with possibly conformity (ARCO Australia Ltd. 1972). To the south, the Keep Inlet Formation unconformably overlies the Tanmurra Formation in Bonaparte 1 (Veevers and Roberts, 1968), hence it probably unconformably overlies the Point Spring Sandstone around Weaber Range. The Border Creek Member occurs in the upper part of the Point Spring Sandstone type section, where it is probably a diachronous unit.

Distribution and thickness: The Point Spring Sandstone outcrops in an arcuate belt, extending from north of Utting Gap to Burvill Point and eastwards through the Weaber Range (Fig. 107). Isolated outcrops are known in the Northern Territory, east of Sorby Hills and southwest of Spirit Hill. Subsurface occurrences are restricted to Bonaparte 2 and Pelican Island 1. The Border Creek Member is recognized in three areas: eastern Weaber Range around the type section; northwest Weaber Range; and 9 km east of Tanmurra Bore.

The incomplete type section is 236 m thick, including 45 m of the Border Creek Member (Veevers and Roberts, 1968). The thickest section, 1.5 km to the west, is 380 m. In Bonaparte 2 and Pelican Island 1 the unit is 180 m and 229 m thick, respectively.

Fossils and Age: The Point Spring Sandstone contains brachiopods, bivalves, plants, diverse trace fossils (Veevers and Roberts, 1968), spores, and pollen. Body and trace fossils are most abundant in parallel-bedded (Fig. 111) and laminated sandstone, and occur rarely in cross-bedded sandstone. Plants dominate in the upper parts of the sequence, with *Phyllotheca*-like forms occurring in the Border Creek Member in eastern Weaber Range. Rare bivalve or brachiopod fragments occur in siltstones.

A late Visean to early Namurian age is indicated by brachiopods from outcrops (Veevers and Roberts, 1968) and microflora in Bonaparte 2 (Kemp and others, 1977). Younger sections may be preserved to the north, since the Point Spring Sandstone is lower Namurian to Westphalian in Pelican Island 1 (ARCO Australia Ltd, 1972; Kemp and others, 1977).

TANMURRA FORMATION

Definition: The Tanmurra Formation is a subsurface unit of sandstone, minor limestone and dolomite. Le Blanc (1964) named the unit and designated the type section from 194 m to 497 m in Bonaparte 1.

Lithology: The type section consists of two carbonate units separated by a sandstone, 256 m thick. The lower carbonate (20 m thick) consists of very fine- to fine-grained, partly peloidal sandy calcarenite. The quartz sandstone is very fine- to medium-grained, calcareous at the top and dolomitic at the base. It includes interbeds of calcilutite, calcarenite, dolomite, and calcareous siltstone. The upper carbonate (26 m thick) consists of slightly sandy, very fine- to fine-grained calcarenite at the base, overlain by sandy and silty oolite. The oolite grades from calcirudite (base) to calcarenite (top).

The unit is sandier in the south and more calcareous in the north (Laws and Brown, 1976). In Bonaparte 2, the upper and lower carbonates

are missing, and the unit consists of sandstone with lesser interbedded dolomite, siltstone, and shale. The sandstone is very fine to fine grained, silty, clayey, calcareous, and dolomitic. Lower parts of the formation contain very coarse-grained and very poorly sorted sandstone, with silty and sandy dolomite. In Pelican Island 1, the Tanmurra Formation consists of interbedded sandstone, limestone and minor shale (ARCO Australia Ltd, 1972). The sandstone is generally fine grained. It grades into siltstone, and medium- to coarse-grained beds are rare. Limestones consist of sandy, shaly and oolitic calcilutites, which are dolomitic in the upper part of the unit.

Stratigraphic relationships: The Tanmurra Formation is conformable on the Milligans Formation, below, and is overlain either conformably by the Point Spring Sandstone or unconformably by the Keep Inlet Formation. In the type section, the Tanmurra and Milligans Formations are lithologically gradational and the contact is chosen at the base of the lower carbonate unit (Le Blanc, 1964). Loughnan (*in* Veevers and Roberts, 1968) noted a distinct mineralogical break at this horizon. In Bonaparte 2 the boundary is well defined. The Tanmurra Formation is conformably and gradationally overlain by the Point Spring Sandstone in Bonaparte 2 and Pelican Island 1, forming coarsening-up sequences. In Bonaparte 1, the Upper Carboniferous to Lower Permian Keep Inlet Formation unconformably overlies the Tanmurra Formation. Based on stratigraphic position, lithology, and age the Tanmurra Formation is probably the subsurface equivalent of the Utting Calcarenite, Burvill Formation, and lower part of the Point Spring Sandstone.

Distribution and thickness: The Tanmurra Formation occurs in the central part of the basin, down dip from Weaber Group outcrop. The formation is present in all oil-exploration wells in the Bonaparte Basin, except Ningbing 1 and Spirit Hill 1. Complete, non-eroded sections in Bonaparte 2 and Pelican Island 1 are 295 m and 465 m thick, respectively, possibly reflecting thickening to the north. The type section is 302 m thick.

Fossils and age: The type section contains foraminifers, ostracods, rugose corals, brachiopods and crinoids (Le Blanc, 1964). Foraminifers indicate a late Visean to early Namurian age (Mamet and Belford, 1968). Brachiopods in Kulshill 1 indicate a similar age (Veevers and Roberts, 1968). Microflora in Pelican Island 1 indicate a Visean age (ARCO Australia Ltd, 1972; Kemp and others, 1977).

FACIES ANALYSIS OF THE WEABER GROUP

The Weaber Group is a very thick coarsening-up sequence divided into shale-dominated and sandstone-dominated sequences. Within each sequence, facies and interpreted depositional process are similar, and depositional environments are related. The shale-dominated sequence, which

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Figure 111. Bedding plane in parallel-bedded sandstone (facies *Sa*) completely covered with crawling traces. Point Spring Sandstone, central Weaber Range, 4.5 km east-northeast of Point Spring.

TABLE 11. SANDSTONE FACIES, SHALE-DOMINATED SEQUENCE, WEABER GROUP

	FACIES	*WAGGON CREEK*	*OPIK HILL*	*TANMURRA BORE*
A	Massive to bedded conglomerate: matrix and clast supported, pebble to boulder clasts, moderately sorted	Beds 0.2–1.5 m, sequences <15 m; massive, irregular bed contacts, minor parallel stratification, rare vertical clasts; Quartz (Q) <15 cm; shale (S) <20 cm; dolomite (D) <70 cm, local boulders to 15 m; abundance: Q >S >D	Sequences 1–6 m; massive, poorly bedded Q <6 cm, S <25 cm	Massive, medium to coarse sandstone matrix, poor sorting; Q <10 cm, S <1 m; rare slump folds
B	Interbedded conglomerate and sandstone: clast and sand supported, pebble-cobble conglomerate; fine to coarse sandstone, moderate to poor sorting	Beds 0.5–1.0 m, sequences <10 m; normally graded and well-defined interbeds. Conglomerate: eroded base, massive, minor parallel bedding, rare cross-bedding. Sandstone: massive, laminated, rare cross-bedding, some granule lags; Q, S, D, <15 cm, fossiliferous	Beds 0.3–6.0 m, sequences 1–17 m; normally graded interbeds rarely inversely graded. Conglomerate: eroded and non-eroded base, massive, minor parallel bedding, rare load casts. Sandstone: massive, rare cross-beds, ripples; some quartz and shale pebble lags, Q <6 cm, S <20 cm,	
C	Pebbly sandstone: fine to coarse sandstone, pebbly, moderate to poor sorting	Mainly fine to medium; beds 0.3–1.5 m, sequences <10 m. Base: eroded and non-eroded, normally graded, massive. Top: massive, rare parallel-laminated, low-angle cross-bedded; Q <12 cm, S locally abundant, D rare, fossiliferous	Mainly medium to coarse; beds 2–6 m. Base: as for Waggon Creek. Top: massive, minor laminated; Q <6 cm, S <12 cm (rare boulders)	
D	Massive sandstone: fine to coarse grained, poor to well sorted, slightly pebbly	Beds 0.5–1.5 m, sequences <30 m; eroded base, scour and tool marks, massive, normally graded, lag conglomerate; minor dish structures, cross-bedded; rare laminated and interference rippled top; Q <6 cm, S <12 cm, fossiliferous		
E	Thick structured sandstone: fine to coarse grained, moderately sorted, pebbly base	Beds 1–1.5 m, sequences 10 m; mainly medium to fine grained, non-eroded base, normally graded, laminated, interference ripples; Q, S <4 cm.	Beds 1–2.5 m, sequences <4.5 m; mainly medium to coarse grained, normally graded and non-graded (thinner beds), laminated, parallel-bedded; rare cross-bedded, Q, S <4 cm	
F	Thin structured sandstone: fine to medium base, rare coarse sandstone and pebble conglomerate, minor silty top	Beds <0.3 m, sequences <25 m; mainly massive, flute and tool marks common; minor normal grading, ripple cross lamination and interference ripples; rare ferruginized shale concretions; fossiliferous shales, wood in sandstone		Beds <0.2 m; load casts, flutes, and brush marks, massive, normally graded, lamination; rare interference and longitudinal ripples, parting lineation;
G	Shale	Sandy, fossiliferous	Beds <2 m, sequences <6 m; massive and laminated; minor thin normally graded sandstone interbeds; bioturbated; also caps normally graded beds	

consists of Milligans and Waggon Creek Formations, was deposited in basinal to offshore shelf environments, including submarine fans. The sandstone-dominated sequence consists of Utting Calcarenite, Burvill Formation, and Point Spring Sandstone. In these units deposition occurred in shelf and deltaic environments.

The facies and depositional environment of the Tanmurra Formation are inferred to be similar to those in the sandstone-dominated sequence.

SHALE-DOMINATED SEQUENCE

The shale-dominated sequence consists of shale and minor sandstone. Sandstone occurs as thin to very thick bodies reaching about 700 m in Keep River 1. The facies codes used in this bulletin cannot be easily applied to sandstone facies of submarine-fan deposits. Instead, the sandstone facies are coded by letters, (facies *A* to *G*), in a scheme similar to that utilized by Howell and Normark (1983) in their review of submarine fans.

Shale facies

Shale comprises most of the Milligans Formation. It is tens to hundreds of metres thick (Fig. 108), and occurs over a large area. The shale may be silty and contains a diverse microflora and microfauna.

Deposition occurred in quiet water, below wave base, and the diversity of the fauna indicates open-marine conditions. Local, thin, gypsiferous and carbonate beds led Crowe (*in* Laws, 1981) to suggest estuarine deposition. However, the thickness and regional extent of the shale (Fig. 109) argue against such an origin (Clifton, 1982).

Sandstone facies

Seven facies, identified by Beere (1984) in the Waggon Creek Formation at Waggon Creek, can be recognized in the two other outcrop areas in Western Australia. Detailed facies descriptions for each area are given in Table 11 and general descriptions follow.

Facies *A* consists of massive to bedded, matrix-supported and clast-supported conglomerate. Clasts are mainly quartzite and siltstone boulders. Dolomite boulders (up to 15 m) are locally common and include stromatolitic, laminated, oolitic, massive and sandy types, with a single cobble of *Syringopora*. Minor parallel stratification is defined by tabular clasts, and vertical clasts are rare. Facies *B* consists of graded and sharply interbedded, massive, pebble-cobble conglomerate and fine- to coarse-grained sandstone (Fig. 112). Normal grading, defined by decreasing clast size, or (more rarely) decreasing proportion of clasts, is dominant. Inverse grading occurs at Opik Hill. Minor parallel and cross-bedding occur in the conglomerate; minor lamination, cross-bedding and rare ripples occur in the sandstones.

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Figure 112. Normally graded and interbedded conglomerate and sandstone (facies *B*, shale dominated sequence). Below the hammer, grading is poorly developed and massive sandstone contains pebble lags. Above the hammer, normally graded conglomerate passes upwards into poorly parallel-bedded sandstone then laminated sandstone. Waggon Creek Formation reference section.

Facies *C* consists of normally graded, pebbly sandstone. There is a gradation upwards from non-eroded, or eroded, pebbly bases, into fine- to coarse-grained massive sandstone, and then rarely into shale. Lamination and low-angle cross-bedding is rare.

Facies *D* consists of fine- to coarse-grained massive sandstone and occurs only in the Waggon Creek area. Minor features include scattered pebbles and cobbles at the base of beds, dish structures in the middle, and poor cross-bedding, lamination and ripples at the top.

Facies *E* consists of thick-bedded (1–2.5 m), fine- to coarse-grained, structured sandstone (Fig. 113). The base is graded and may be pebbly; middle and upper parts of beds are laminated, parallel bedded, or rarely cross-bedded, and may include pebble lags; interference ripples occur at the top.

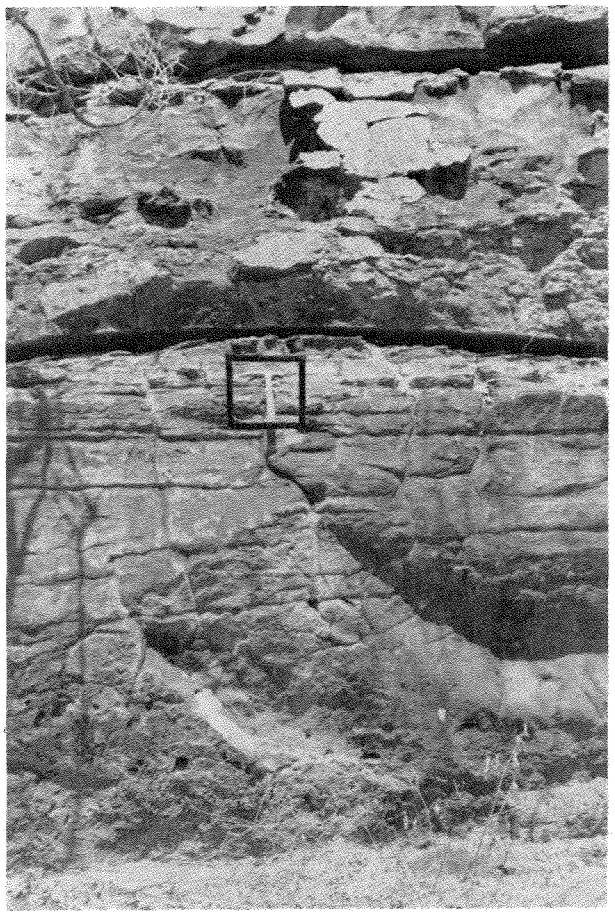

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Figure 113. Thick structured sandstone (facies *E*, shale-dominated sequence). At the base of the exposure, normally graded pebbly sandstone (with shale clasts weathering to voids) passes upwards into massive sandstone, then parallel-bedded and laminated sandstone. Shale forms the overlying recessive unit in shadow. Waggon Creek Formation, 3 km east of the type section.

Facies *F* consists of thin-bedded (less than 0.3 m), fine- to medium-grained, structured sandstone. Sole marks are common, including flute, tool and brush marks, also load casts. The beds are usually massive and may be normally graded. They include ripple cross-lamination, longitudinal and interference ripples, and parting lineation may occur at the tops of beds.

Facies *G* consists of shale and siltstone and is poorly known. At Tanmurra Bore thick beds are both massive and laminated, and include thin horizons of facies *F*, also bioturbation.

Depositional processes have been interpreted for all facies in the Waggon Creek area by Beere (1984) and are summarized below. All sand and conglomerate facies were deposited by turbidity currents and other mass-gravity flows. Clast-supported massive conglomerates (facies *A*) were probably lag deposits formed either on relatively steep slopes (Walker, 1978) or at a marked change in slope, where current competence rapidly decreased (Beere, 1984). Matrix-supported conglomerates in facies *A* and those with upward projecting clasts were probably deposited by debris flows (Middleton and Hampton, 1973; Walker, 1978).

Normal grading and the sequence of structures in most other conglomerate and sandstone facies (*B* to *F*) indicate deposition from turbidity currents. Decreasing grain size and bed thickness between the facies indicate deposition from turbidity currents of increasingly distal aspect. Well-defined interbeds of conglomerate and sandstone in facies *B* suggest interrupted deposition from different parts of a turbidity current, or the stacking of deposits from turbidity currents of different loads or flow conditions. The occurrence of granule lags in facies *B* supports the interrupted-deposition hypothesis. Inversely graded deposits (facies *B*) at Opik Hill were probably deposited by debris flows. Massive sandstone (facies *D*) was probably deposited by turbidity currents. Dish structures indicate that any internal structures, which formed early, were obliterated by fluidization in the final phase of deposition (Walker, 1978). Siltstone and shale (facies *G*) were deposited from suspension, where higher energy turbidity-current deposition was absent.

Facies associations

Facies association 1 (FA 1): This comprises the Milligans Formation and consists mainly of shale with minor thin interbeds of limestone, siltstone, sandstone, pebbly sandstone, and conglomerate. Shale was deposited below wave base in an open-marine enviroment. If the coarser clastic interbeds

are of turbiditic origin, as in the other facies associations, then the association was probably deposited in a basin, although the water depth cannot be estimated.

Facies association 2 (FA 2): This forms part of the Waggon Creek Formation. It consists mainly of thin-bedded structured sandstone (facies *F*), locally including massive sandstone (facies *D*) at Waggon Creek and massive conglomerate (facies *A*) at Tanmurra Bore. At Waggon Creek the association is at least 80 m thick. Flaggy outcrop characteristic of this association suggests that shale (facies *G*) is an important component. Turbidity currents deposited most sediment, but late-stage fluidization produced massive sandstones, while debris flows possibly deposited some massive conglomerate.

The association was probably deposited in the middle parts of a submarine fan. Thick, coarser grained facies (facies *A* and *D*) probably represent channel deposits. The finer, thinner bedded facies (facies *F*) represents interchannel deposits. In the interchannel deposits at Tanmurra Bore three flutes and a parting lineation indicate that currents flowed to the north. Shale (facies *G*) accumulated during periods of low clastic input.

Facies association 3 (FA 3): This occurs in the Waggon Creek Formation at Waggon Creek and Opik Hill, where it is generally finer grained and lacks dolomite clasts. The association is dominated by pebbly sandstone (facies *C*) and interbedded conglomerate and sandstone (facies *B*). It is up to 85 m thick at Opik Hill. At Waggon Creek, massive conglomerate (facies *A*) and massive sandstone (facies *D*) are also common, while thin- and thick-bedded structured sandstone (facies *E* and *F*) and shale (facies *G*) are minor. Here, the association fills an east-northeast-oriented channel in the underlying Hargreaves Formation. Dolomite clasts were probably derived both from Cambrian rocks outcropping to the west and, locally, from the Hargreaves Formation (Beere, 1984). At Opik Hill, facies *E* and *G* are common and facies *A* is minor. Clasts include mainly intraformational siltstone and quartzite.

Facies association 3 is interpreted as channel deposits on an upper submarine fan. At Waggon Creek, turbidity currents deposited most sediment, although some of facies *A* was probably deposited by debris flows and facies *D* was affected by late-stage fluidization. The diversity of facies types was probably caused by deposition at differing sites within the channel. Coarse facies (*A,B,* and *C,*) were probably deposited by debris

TABLE 12. LIMESTONE FACIES, SANDSTONE-DOMINATED SEQUENCES, WEABER GROUP

	FACIES	*UTTING CALCARENITE*	*BURVILL FORMATION*
Cm *Csm*	massive sandy	Wackestone, scattered medium quartz; beds 2–3 m; diverse fauna	Wackestone–packstone, minor mudstone and grainstone, scattered medium to very coarse quartz, subangular to subrounded, minor granules and pebbles; isolated beds 0.3–1 m rarely <5 m; diverse fauna, may cap coarsening-upward sequences of facies *Sa*
Ca *Csa*	parallel bedded, sandy	Minor; wackestone, minor packstone, scattered fine to medium quartz; thin to medium bedded, thin to thick beds <3 m; diverse fauna, bioturbated	Minor; wackestone–packstone, scattered coarse to very coarse quartz; thin beds; crinoidal
Ct *Cst*	trough cross-bedded, sandy	Minor; packstone; fine to medium quartz; medium sets <0.3 m medium to thick beds <4 m; diverse fauna	
Ch	laminated	Minor; wackestone, fine to medium quartz; thin beds; possible microbial lamination	

TABLE 13. CONGLOMERATE, SANDSTONE, AND SILTSTONE-SHALE FACIES, SANDSTONE-DOMINATED SEQUENCE, WEABER GROUP

FACIES	*UTTING CALCARENITE*	*BURVILL FORMATION*	*POINT*	*SPRING*	*SANDSTONE*
					Border Creek Member
CONGLOMERATE:					
Gm Massive					Matrix supported, polymodal, bimodal, up to cobble clasts of quartzite and minor siltstone; beds 2–20 m thick; minor planar cross bedding (*Gp*)
SANDSTONE:					
St Trough cross-bedded *Sp* Planar cross-bedded	Minor, *St* only; medium grained, calcareous; medium beds;	Rare, *St* only; medium grained; thin sets, thin to medium sequences; bioturbated	Equal amounts *St* and *Sp*; fine to medium grained, minor very fine and coarse, moderate to well sorted, scattered granules, rare pebbles to 6 cm, minor siltstone intraclasts, rare lags; medium to thick sets, sequences 3–10 m thick and 20–35 m thick, fining-up sequences common; rare body fossils and bioturbation; minor thick contorted and massive beds		*Sp* dominant; fine to medium grained, minor coarse quartz, pebbly, moderately sorted, common siltstone intraclasts; medium to thick sets

Sa	Parallel bedded	Fine to medium grained, well sorted, calcareous thin beds; fossiliferous and bioturbated; minor ripples	Very fine to fine grained, locally medium; scattered coarse quartz and pebbles, locally calcareous; thin to medium bedded; fragmented and *in situ* fossils; diverse bioturbation; minor ripples	Fine to very fine grained, well sorted; range silt to medium grained, rare coarse quartz and granules; very thin to medium bedded <0.3 m, very thick sequences <16 m; common horizontal bioturbation, minor vertical bioturbation and body fossils; minor thin horizons of *St, Sp, Sl,* ripples, and *Sm*	Minor; fine to medium grained, pebbly; thin bedded, medium to thick sequences <3 m
Sh	Laminated		Minor; very fine grained; thin to medium beds <0.5 m, some fining-upward sequences; bioturbated including escape burrows;	Very fine to fine, minor siltstone, well sorted, rare coarse sandstone and shale lenses and beds; beds 2–4 m thick; bioturbation common, some escape burrows	
Sl	Low-angle cross-bedded		Rare; very fine grained; thin to medium beds <0.5 m, erosional base	Very fine to fine grained, well sorted, minor scattered granules; medium sets, medium to thick sequences 0.5–3.0 m; minor bioturbated tops, ripples; associated with facies *Sa, Sh, Fh*	
SHALE:					
Fm	Massive			Minor; beds <0.5 m	Beds <5 m; locally common wood, rare body fossils, bioturbation
Fh	Laminated		Beds <4 m; horizontal and vertical bioturbation; ?interbedded with *Sa*	Beds 0.1–0.5 m, max 1.5 m; horizontal and vertical bioturbation; transitional and interbedded with *Sa*; minor ripples	
Fr	Rippled		Beds <2 m	Minor; beds <0.5 m	

flows and turbidity currents in deeper parts of the channel, and finer, thinner bedded facies were deposited by turbidity currents on channel terraces (facies *C,D,* and *E*), levees (facies *F*), or overbank areas (facies *G*). Channelling of the underlying Devonian and local derivation of large dolomite clasts suggest that deposition took place near the fan head (Beere, 1984). A general easterly transportation direction is indicated by the provenance of some dolomite clasts (from Cambrian rocks to the west and south) and the east-northeast orientation of the channel. At Opik Hill, deposition occcurred on an upper fan, but away from the fan head. Compared to Waggon Creek, the finer grain size of the facies indicates more distal deposition. Turbidity currents deposited most facies, although debris flows deposited some of facies *B*, while facies *G* was deposited from suspension.

Relationship of facies associations: The facies associations may define large-scale sequences. A fining-upward megasequence (FA 3 underlies FA 2) at Waggon Creek, 120 m thick, indicates that the fan has undergone retrogradation or abandonment. In Keep River 1, a coarsening-upward megasequence, 700 m thick, within Milligans Formation indicates there has been fan progradation.

Fan progradation and retrogradation occur in response to several influencss which reflect tectonic and sedimentary history (Howell and Normark, 1982). This history is discussed, later, in relation to the Bonaparte Basin, as part of the description of depositional environment.

SANDSTONE-DOMINATED SEQUENCE

The sandstone-dominated sequence consists mainly of sandstone with minor limestone, shale, siltstone, and conglomerate. Detailed descriptions of facies, recognized within all formations except the Tanmurra Formation, are given in Tables 12 and 13.

Limestone facies

Limestones occur in the Utting Calcarenite, Burvill Formation (Table 12), and Tanmurra Formation. Wackestone and packstone textures in most facies indicate a low-energy to low-winnowing environment. Absence of bedding in massive limestone (facies *Cm*) is typical of subtidal carbonates (Enos, 1983). Parallel and trough cross-bedded limestone (*Ca* and *Ct*) formed as plane beds and sinuous crested dunes, reflecting current activity above wave base. Laminated limestone (facies *Ch*) indicates either low-energy suspension deposition at (or near) wave base, or the lamination may be of microbial origin suggesting intertidal-supratidal deposition.

Sandstone and conglomerate facies

Sandstone facies occur in all formations in the sand-dominated sequence (Table 13). Planar and trough cross-bedded sandstone (*Sp* and *St*) was deposited as straight and sinuous crested dunes in two environments. Thin (<0.5 m), calcareous, or fossiliferous horizons were probably deposited on an upper shoreface. Thicker, coarse-grained, and more poorly sorted horizons (lacking fossils) were probably deposited in a fluvial environment. Rare fossils in this facies, in the Point Spring Sandstone, reflect a slight marine influence. Contorted foresets indicate that syndepositional deformation and massive beds (facies *Sm*) may result from the total loss of foreset definition by severe deformation. In lower parts of the Point Spring Sandstone (localities 929, 931, 942, 944, 963, 967, 968, 971; Fig. 107) fluvial-transport directions were

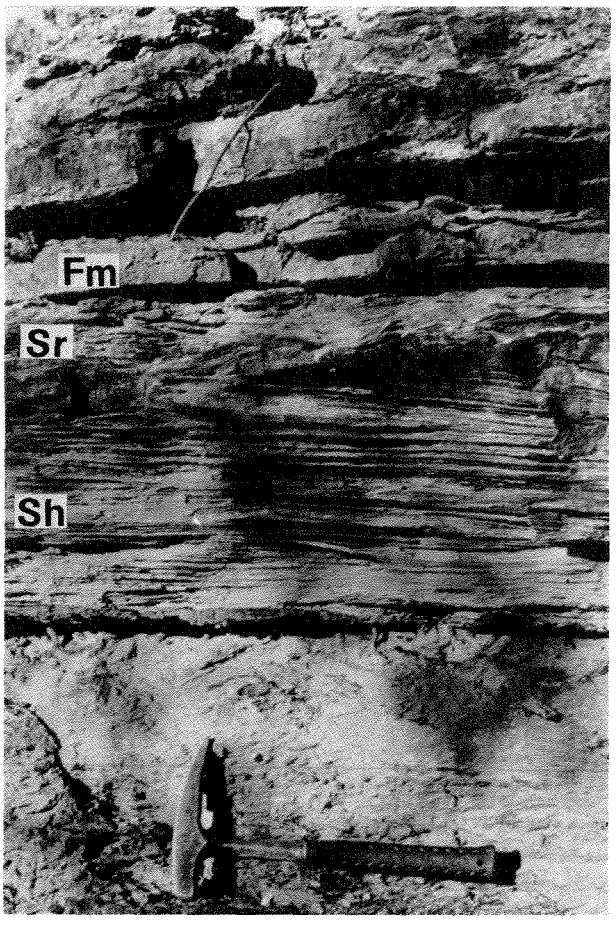

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Figure 114. Intensely bioturbated sandstone is sharply overlain by laminated sandstone (facies *Sh*). This fines upwards into ripple cross-laminated sandstone (*Sr*) then bioturbated siltstone (*Fm*) forming the recessive unit. Burvill Formation, 1 km northeast of Opik Hill.

mainly to the east-northeast, to the northeast at Weaber Range, and to the north and northeast at Tanmurra Bore. Higher in the sequence (localities 961, 969, 970) azimuths are oriented between northwest and northeast. In the Border Creek Member palaeocurrent directions are oriented to the north.

Parallel-bedded sandstone (facies *Sa*) was deposited as moderate- to high-energy plane beds in both shoreface and continental environments. Interbedding of thin fossiliferous beds with shales in the Burvill Formation indicates probable lower shoreface deposition. Thick, fossiliferous horizons lacking interbedded shale, in the Point Spring Sandstone and Utting Calcarenite, indicate higher energy, mid- to upper-shoreface deposition. Periods of varying energy are reflected by thin interbeds of trough, planar, and low-angle cross-bedding, massive bedding, and ripples. Fining and thinning-upward sequences probably reflect shoreface deepening. In the Border Creek Member, facies *Sa* is non-fossiliferous and is associated with fluvial dunes (*St* and *Sp*) indicating deposition as high-energy longitudinal bars.

The very fine grain size and fossils in most parallel-laminated facies (*Sh*) indicate deposition as low- to moderate-energy plane beds, probably on a lower shoreface.

Initial rapid sedimentation is reflected by escape burrows and thin sequences, which fine upwards into rippled and laminated siltstone in the Burvill Formation (Fig. 114).

Low-angle cross-bedded sandstone (facies *Sl*; Fig. 115) indicates moderate- to high-energy deposition as undulating bed forms or as hummocks and swales. The similarity of this facies to hummocky cross-stratification, together with the eroded base, suggest rapid deposition (Harms and others, 1982). Intense bioturbation at the tops of some beds occurred during depositional stillstands. In the Point Spring Sandstone, associated shoreface and offshore deposits (facies *Sa, Sh,* and *Fh*) indicate lower shoreface deposition.

Massive conglomerate (facies *Gm*) in the Border Creek Member indicates very high-energy deposition as longitudinal bars in a river channel.

Siltstone and shale facies

Siltstone and shale facies occur in all formations except the Utting Calcarenite (Table 11). Massive and laminated siltstone (*Fm* and *Fh*) was deposited from suspension, and rippled siltstone (*Fr*) represents low-energy traction deposition. Fossiliferous facies *Fr* and *Fh* associated with shoreface deposits, in the Point Spring Sandstone and Burvill Formation, probably represent offshore-marine deposition. Laminated siltstones (*Fh*) sometimes cap fining-upward sequences. These are interpreted as fluvial deposits, overlain by abandonment deposits. In the Border Creek Member, the lack of fossils in facies *Fm* and the association with fluvial deposits suggest overbank deposition.

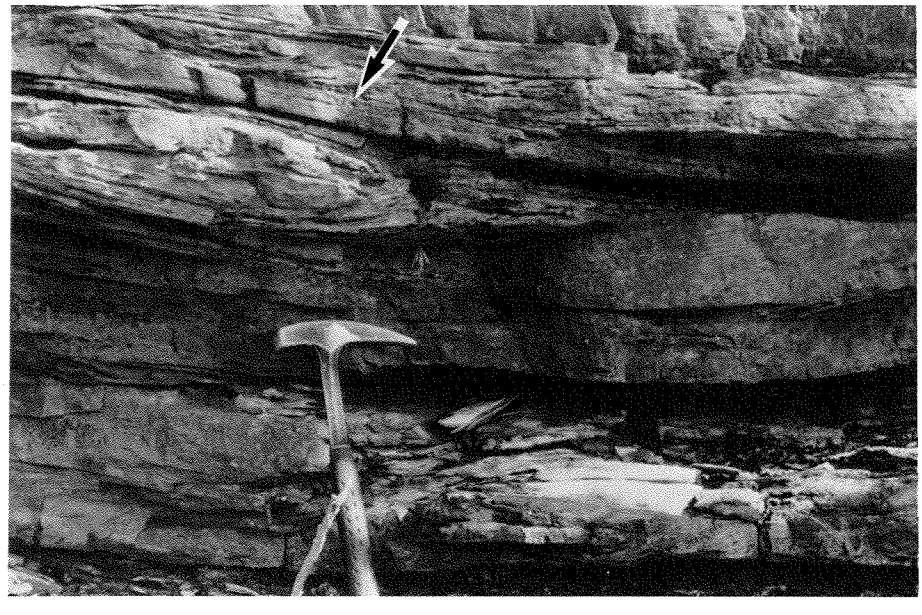

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Figure. 115. Low-angle cross-bedded sandstone (facies *Sl*). Convex-upward lamination (arrowed) makes this facies similar to hummocky cross-stratification. Point Spring Sandstone, 16 km west-northwest of Point Spring.

Facies associations

Facies association 4 (FA 4): This comprises the Utting Calcarenite and consists mainly of parallel-bedded sandstone and sandy limestone (*Sa* and *Csa;* Fig. 110). Minor facies include massive, laminated, and trough cross-bedded sandy limestone (*Cm, Ch,* and *Ct*) and trough cross-bedded sandstone (St). The association consists of thick to very thick beds of carbonate, and thin to medium interbedded clastic and carbonate facies. Bioturbation and macrofossils are common.

Deposition probably occurred on a clastic-influenced open shelf. The diverse fauna indicates open-marine conditions. Textures and structures in the sandstones and carbonates indicate moderate- and low-energy deposition above wave base, mainly as plane beds and sinuous crested dunes. Some laminated limestones (facies *Ch*) were possibly microbial mats in an intertidal-supratidal zone. Thick sequences of interbedded sandstone and carbonate formed during a period of high overall clastic input. The carbonates on this sequence were deposited during periods of reduced clastic input in a low-energy environment.

Facies association 5 (FA 5): This comprises the Burvill Formation and consists mainly of interbedded, thin, parallel-bedded sandstone (facies *Sa*), and laminated siltstone or shale (*Fh*). Minor facies include laminated sandstone (*Sh*), massive and parallel-bedded limestone (*Cm* and *Ca*), and rare rippled siltstone (*Fr*), trough cross-bedded sandstone (*St*) and low-angle cross-bedded sandstone (*Sl*). Coarsening-upward sequences 2–7 m thick, (sections 939, 976; Fig. 110) have facies *Fr* at the base, passing into *Fh* then *Sa*. Bedding in facies *Sa* may also thicken upwards. Limestone which caps the sequence contains scattered quartz reworked from underlying facies. Fining-up sequences up to 0.5 m thick occur within facies *Sh* (Fig. 114). The association contains diverse body and trace fossils.

Facies association 5 represents lower shoreface and offshore deposition in a delta front or prodelta environment. The diverse fauna indicate an open-marine environment. The green algae show that the water depth was less than 30 m (Wray, 1977). Most clastic facies indicate low-energy deposition as plane beds (*Sa, Sh,* and *Fh*) or ripples (*Fr*) probably in lower shoreface and offshore environments. High-energy periods formed sinuous crested dunes (*St*) and undulating bed forms (*Sl*). Facies *Sl* and fining-up sequences in *Sh* indicate rapid deposition, possibly from storms or floods from a shoreward delta. Larger scale coarsening-up sequences reflect shallowing by shoreface progradation. Limestone was deposited during periods of low clastic input, and pebbles were reworked from the sandy substrate.

Facies association 6 (FA 6): This comprises the Point Spring Sandstone and consists mainly of trough and planar cross-bedded sandstone (*St* and *Sp*) and parallel-bedded sandstone (*Sa*; Fig. 110). Minor facies include laminated, massive and rippled siltstone or shale (*Fh, Fm,* and *Fr*), and laminated and low-angle cross-bedded sandstone (*Sh* and *Sl*). Facies *Sa* lacks shale interbeds, and fining and thinning-up sequences (Fig. 110) are common in facies *St* and *Sp*. Body and trace fossils occur in most facies except *St* and *Sp*.

Thick coarsening and fining-up sequences of facies are common in this association (Fig. 110). Coarsening-up sequences (up to 12 m thick) pass from a thin lag of medium to coarse sand and pebbles into thin facies *Fh*, then *Sl* and bioturbated *Sa*, which becomes thicker bedded upwards. Non-fossiliferous facies *St* and *Sp* may cap the sequence. Fining-up sequences, 3–8 m thick, occur in horizons 8–11 m thick. Facies *St* and *Sp* (with rare body fossils) infill channels, and upper parts of the sequences consist of up to 4 m of bioturbated and fossiliferous facies *Sa, Sl, Fh,* and *Fr* (Fig. 110).

This association was deposited in interfingering shoreface and fluvial environments, including distributary mouth bars, crevasse-splays, and abandoned distributary channels. The absence of siltstone in facies *Sa* indicates mid- to upper-shoreface deposition. Fining-up sequences in fluvial facies *St* and *Sp* were caused by channel migration or abandonment. Facies *Sh* and *Sl* were probably deposited by storms on the lower shoreface, and facies *Fm, Fr* and *Fh* represent offshore deposition.

Coarsening-up sequences represent shoreface shoaling, occasionally into fluvial environments. In a deltaic environment both distributary mouth bars and crevasse-splays form coarsening-up sequences (Coleman and Prior, 1982). Crevasse-splays are thinner and have more fine sediment at the base of the cycles, hence it is likely that most coarsening-up cycles in this association are distributary mouth bars. Fining-up sequences show an upward transition from fluvial to low-energy marine facies, characteristic of abandoned distributary channels (Coleman and Prior, 1982). The marine facies here may represent lagoon, offshore, or shoreface environments.

Correlation of three sections in central Weaber Range (Fig. 110; sections 967, 971, 976)

using basal lags and limestones illustrates the lenticular nature of fluvial sandstone; it also shows a composite sequence (about 35 m thick) consisting of distributary mouth bar, fluvial, and abandoned channel environments. Palaeocurrent azimuths are to the northeast (Fig. 107), parallel to the line of section. In section 967, a distributary mouth bar (1–9 m) is overlain by shoreface sands (9–12 m) and a thick sequence of fluvial sands with minor shoreface deposits (12–40 m). This sequence passes down depositional dip, over a distance of 2.3 km, into shoreface sands and a distributary mouth bar, with a lenticular fluvial channel between 15 m and 20 m in section 971. In this section a lag (at 20 m) marks the base of the second sequence, representing the progradation then abandonment of a major distributary system. The lag is overlain by a distributary mouth bar (20–24 m) to fluvial sequence (24–46 m). If a similar sequence occurs in section 967, then the fluvial sands are overlain by two abandoned distributary channels (64–75 m).

Facies association 7 (FA 7): This comprises the Border Creek Member and consists mainly of planar cross-bedded sandstone (*Sp*) with lesser massive conglomerate (*Gm*), massive siltstone (*Fm*), trough cross-bedded sandstone (*St*), and parallel-bedded sandstone (*Sa*). Body fossils occur rarely in facies *Fm*. Two subsidiary facies associations are recognized: 7A and 7B. Facies association 7A consist mainly of thick beds of facies *Gm* and *Fm*, with minor facies *Sa*. It is lenticular and probably diachronous in the eastern and central Weaber Range. A fining-up sequence, 16 m thick, above 270 m in section 967, consists of facies *Gm* (base), *Sa*, and *Fm* (top). Facies association 7B consists mainly of facies *Sp* with minor *Gm*, *St*, and *Sa*, and is similar to facies *Sp* in the Point Spring Sandstone. Facies *Gm* is thinner and the clasts are smaller than in facies association 7A. Two thinning and fining-up sequences 5–8 m thick between 305 m and 318 m in section 967 consist of facies *Gm* at the base and pass into facies *Sp* (Fig. 110).

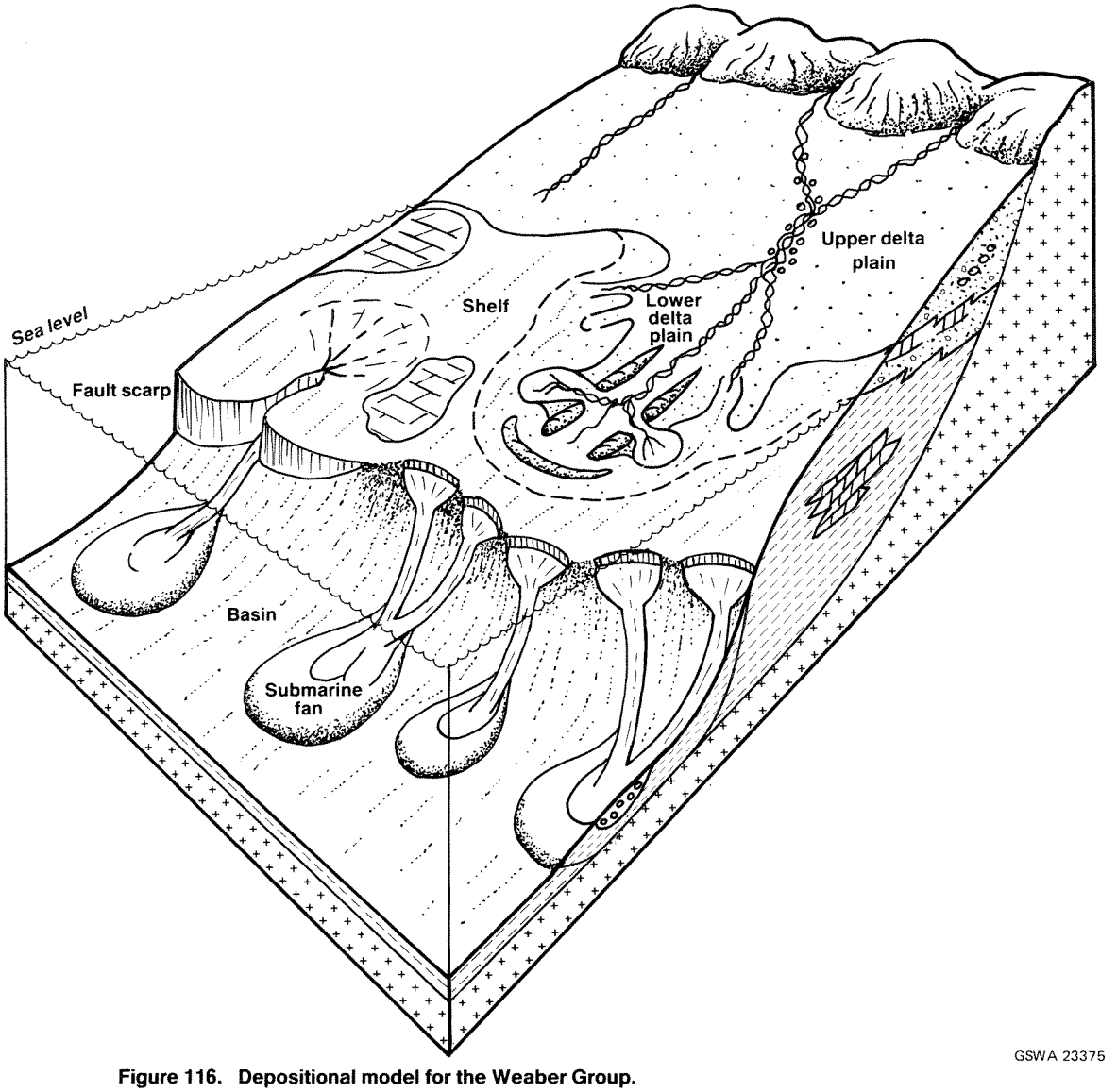

Figure 116. Depositional model for the Weaber Group.

Facies association 7 was probably deposited in broad, shallow, braided rivers. Facies *Sp, Sa,* and *Gm* were deposited as sandwaves, and longitudinal sand and gravel bars; and they show that there was little channel to bar-top topography. However, high-energy, sinuous, crested dunes (facies *St*) may have formed in rare deep channels, and facies *Fm* was deposited from suspension in overbank areas or in abandoned channels. The facies assemblage is similar to that in broad shallow rivers, characterized by the Platte River (Miall, 1982). Facies associations 7A and 7B represent gravel and sand-dominated reaches, respectively. The interbedding of facies *Gm* and *Fm* was possibly caused by the relatively sudden abandonment of the gravel reach and infill with siltstone. Thinner fining-up sequences (7B) were caused by bar aggradation and thick sequences (7A) possibly represent gradual channel abandonment.

DEPOSITIONAL ENVIRONMENT

The Weaber Group is a very thick coarsening and shallowing-up sequence, formed by delta progradation into a basin. The sequence consists of offshore-to-basinal shales (Milligans Formation) which underlie shoreface and deltaic sandstones (Burvill Formation, Point Spring Sandstone, Tanmurra Formation. Lenticular units include submarine-fan sandstone and conglomerate (Waggon Creek Formation), open-shelf carbonates (Utting Calcarenite) and braided-fluvial sandstone and conglomerate (Border Creek Member).

The Weaber Group depositional system consisted of a fluvially dominated delta, with a mud and carbonate shelf, separating a deep-water basin which contained submarine fans (Fig. 116). The association of the shales, with both submarine fans and shoreface to offshore sediments, suggests deep basin and offshore shelf deposition, respectively (Milligans Formation).

Submarine-fan deposition occurred in both upper-fan channels and mid-fan supralobes (Waggon Creek Formation). At Waggon Creek, channel sediments fill a valley eroded into Devonian rocks, indicating deposition in a feeder canyon at the fan head. The large size of conglomerate clasts and local derivation from older Palaeozoic rocks, suggest that fan sediments were fault derived. The easterly orientation of the canyon and its proximity to faults, immediately to the west, indicate that these faults were active although the fining-up retrograding megasequence indicates there was limited movement. Conglomeratic submarine fans in similar basin-fill sequences, such as the Californian borderland basins, were deposited at the toes of steep non-depositional fault scarps in water greater than a few hundred metres deep (van de Kamp and others, 1974; Rupke, 1978).

The sandy nature of the Tanmurra and Spirit Hill fans indicates derivation from a delta, with penecontemporaneous erosion of surrounding shales to provide intraclasts. Slumps on the delta front initiated turbidity currents and (as with other delta-fed fans) downslope transportation possibly occurred in several gullies rather than a well-defined canyon (Howell and Normark, 1982). Limited palaeocurrent data indicate northerly transport on the Tanmurra fan. In Keep River 1, the thick coarsening-up megasequences reflect continuous sediment supply (probably from a delta) and fan progradation. The areal extent of the fans is unknown. The size of modern fans is proportional to the amount of sediment supplied (Howell and Normark, 1982). Hence, the locally derived Waggon Creek fan was probably the smallest, while the largest was the Keep River fan. Most fans in restricted basins do not exceed 100 km in radius (Howell and Normark, 1982).

Shelf sedimentation consisted of carbonate and clastic deposition. Away from the delta on the open shelf, carbonates accumulated above wave base (Utting Calcarenite). Periodic influx of clastics was caused by storm remobilization from the delta, or delta floods. Nearer the delta, carbonate deposition was reduced and fine-grained sandstone and shale were deposited in lower shoreface to offshore environments (Burvill Formation). Green algae in the carbonates indicate a water depth of less than 30 m. Thin fining-up sequences possibly represent delta-flood periods. Larger scale coarsening-up sequences, representing shoreface shallowing, possibly reflect sediment input from active distributary channels on the delta plain.

Shoreward, the prodelta passed into a delta plain (Point Spring Sandstone). Both fluvial and wave processes are evident but the delta was probably fluvially dominated. Subaqueous and lower delta-plain deposition occurred in shoreface and fluvial environments, distributary mouth bars, crevasse splays, and abandoned distributary channels. Very thick (35 m) coarsening and fining-up facies sequences reflect the establishment and abandonment of major distributary systems. The upper delta plain consisted of shallow braided rivers where most reaches were filled with sand, but gravel occurred in others. Limited lateral migration led to lenticular bodies of the distinctive conglomerate.

CHAPTER 7

Late Carboniferous-Early Permian of the Bonaparte Basin

INTRODUCTION

The Late Carboniferous to Early Permian sequence in the onshore part of the Bonaparte Basin, in Western Australia, has been referred to as Keep Inlet Formation (Guillaume, 1955), whereas in the Northern Territory and offshore it is referred to as the Kulshill Formation (Duchemin and Creevey, 1966). The former name has precedence, having been defined by Veevers and Roberts (1968) prior to the Kulshill Formation (Hughes, 1978). However, the later name has widespread useage in the offshore Bonaparte Basin. The name "Keep Inlet Formation" is here restricted to the onshore sequence in Western Australia.

KEEP INLET FORMATION

Definition: The Keep Inlet Formation consists of sandstone, shale, and minor conglomerate. Glover and others (1955) proposed "Keep Inlet Beds" for Permian sediments in the Keep River area. Guillaume (1966) first published the name with a brief lithological description. He gave the stratigraphic position as conformably below the "Sugarloaf Formation" ("Fossil Head Formation") and unconformably above the Weaber Group. Veevers and Roberts (1968) formalized the name and designated a type locality 2.1 km northeast of Cleanskin Bore (15°03′S, 128°58′E). Exposures here are very poor and the contacts with overlying and underlying units are not known. Shallow, coal-exploration drilling in the type area reveals shale underlain by sandstone. Similar rocks in Keep River 1, between 0 m and 480 m, were chosen as a reference section by Beere and Mory (1986).

Although "Kulshill Formation" has a widely accepted use in the offshore Bonaparte Basin, it is not used in this bulletin because Keep Inlet Formation has precedence, at least in the onshore part of the Bonaparte Basin in Western Australia.

Lithology: Sandstone, shale and conglomerate occur in sequences dominated by either shale or sandstone. The shale-dominated sequence in Keep River 1 (at 0–219 m) consists predominantly of silty shale with minor beds of siltstone, very fine-grained sandstone, coarse-grained pebbly sandstone, and coal beds 1.5 to 3 m thick (Caye, 1969). At the type locality only float is found; drilling shows that the area is underlain by carbonaceous and glauconitic mudstone and shale, with some very thick (< 30 m) sandstone beds (Williams, 1982; McBain, 1982). The float consists of pebbles and boulders (up to 1 m diameter) of diverse exotic lithologies and calcareous sandstone. The erratic blocks are rounded and some have striated facets. Quartzite clasts are dominant and other rock types include fine- and coarse-grained pink granite, chert, gneiss, pegmatite, limestone, silicified granule-pebble conglomerate, and mylonite. The calcareous sandstone is very fine to fine grained, well sorted, and feldspathic. It contains chert and volcanic grains, scattered pebbles, granules, and green mudflakes. Most sandstone blocks are massive but parallel bedding and ripple cross-lamination also occur.The calcareous sandstone contains some erratic blocks, but the absence of calcareous beds in the subsurface suggests these blocks have also been reworked.

The sandstone-dominated sequence occurs in Keep River 1 (at 219–480 m), Bonaparte 1 (at 0–194 m), and on the Burt Range Shelf. In Keep River 1, it consists of two fining-upward sequences separated by a dark-grey shale at 400–439 m. Fine- to medium-grained feldspathic sandstone in the upper sequence becomes pebbly and poorly sorted with depth. The lower sequence grades downwards from fine sandstone to coarse-grained sandstone. In Bonaparte 1, a silty and micaceous shale (at 76–90 m) splits the sand sequence and it may correlate with the middle shale in Keep River 1. The upper sandstone is medium to very coarse grained and the lower sandstone is medium to coarse grained, with lithic fragments between 90 m and 119 m.

Outcrops on the Burt Range Shelf are correlated with the Keep Inlet Formation, based on similar lithologies and the occurrence of dropstones in shale. At Burt Range and Milligans

Hills, the sandstone-dominated sequence consists of sandstone, with minor shale and conglomerate (Fig. 117). The sandstone is a medium- to fine-grained, well-sorted quartz arenite, with minor matrix and lithic grains of quartzite. It occurs mainly in very thick, laminated or massive beds. Trough and planar cross-bedding, and parallel bedding are minor; low-angle cross-bedding and ripple cross-lamination are rare. Thick beds (up to 15 m) of massive or laminated shale may be silty and, locally, may contain dropstones up to 10 cm in diameter. Bioturbation is rare. Conglomerate is clast-supported, polymodal, or bimodal, and consists of subrounded to well-rounded quartzite pebbles and boulders (<0.7 m diameter). The conglomerate occurs in lenses up to 25 m thick, which may be massive, parallel bedded, or contain very thick planar cross-beds.

At Spirit Hill the unit consists of sandstone and pebbly sandstone, with minor conglomerate and shale. Compared to Burt Range, the sandstone is coarser and texturally less mature. It contains minor quartzite, chert, lithic grains of shale, and rare feldspar. Medium to thick planar cross-bedding is dominant, with minor low-angle cross-bedding, lamination and ripples, with rare contorted beds. Conglomerate and shale are similar to those at Burt Range.

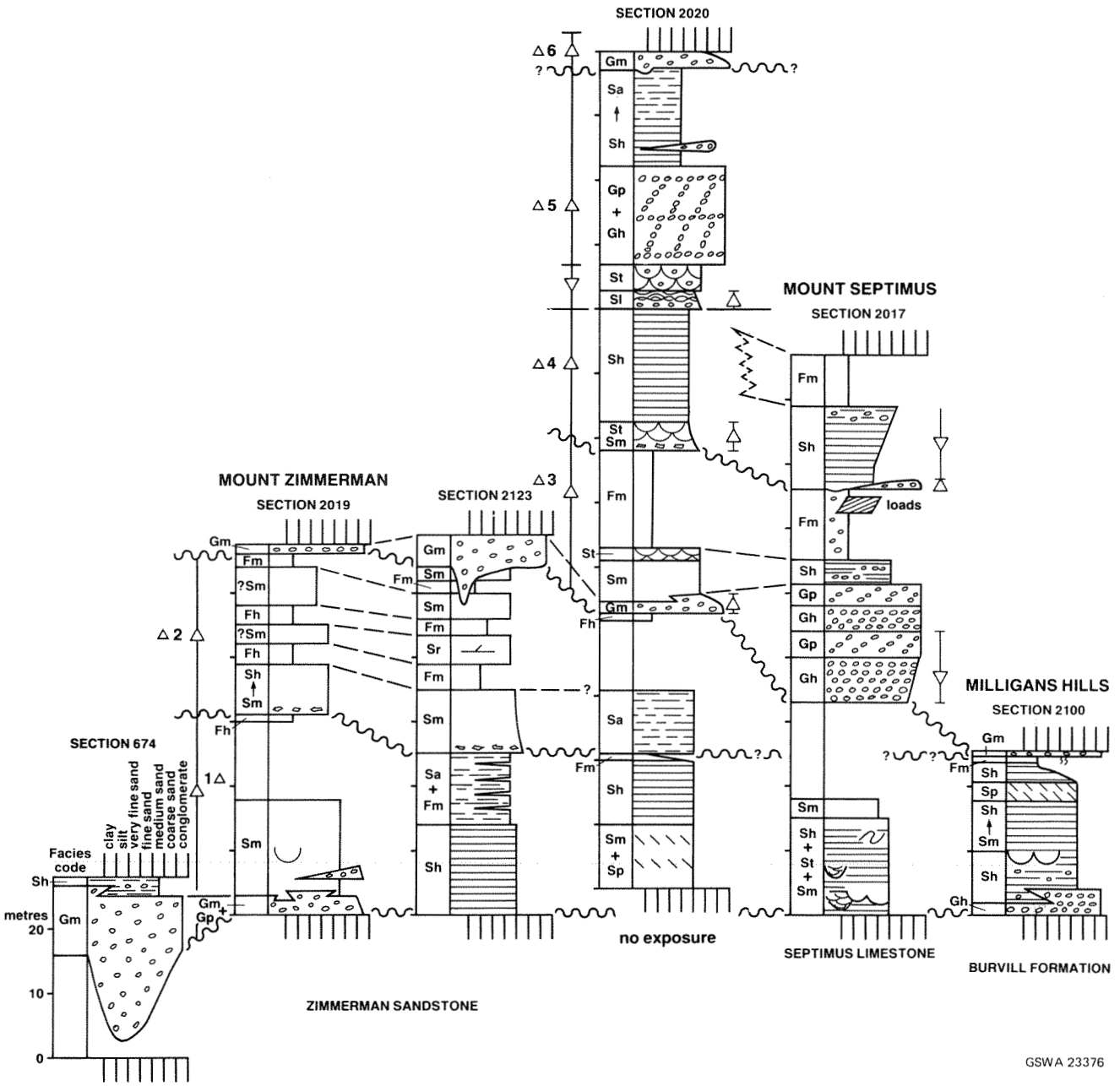

Figure 117. Measured sections of the Keep Inlet Formation with six fining-up cycles (△ 1—6) identified. Location of sections in Figure 93, facies codes in Tables 1 and 8, key to symbols in Figure 3.

On the coast at "The Needles", a coarsening-up sequence (25 m thick) of siltstone and sandstone is tentatively identified as Keep Inlet Formation. At the base, laminated micaceous siltstone with granule horizons is overlain by 20 m of ferruginized medium- to very coarse-grained pebbly lithic sandstone. The sandstone contains scattered quartzite pebbles and cobbles, together with a suite of lithic grains similar to that at Spirit Hill.

Stratigraphic relationships: The Keep Inlet Formation overlies the Langfield Group with angular unconformity. It also overlies the Weaber Group, but with an unconformity which locally disappears to the north. At Burt Range the unit oversteps the Zimmerman Sandstone so that it overlies the Septimus Limestone at Mount Septimus. It overlies the Waggon Creek Formation at Spirit Hill and the Burvill Formation at Milligans Hills. In Keep River 1 and Bonaparte 1, the unit unconformably overlies the Tanmurra Formation (Veevers and Roberts, 1968; Caye, 1969). To the north in Pelican Island 1, Namurian and ?Westphalian sandstone and shale, here designated Point Spring Sandstone, are probably conformably overlain by the Keep Inlet Formation (ARCO Australia Ltd, 1972). To the northeast in Kulshill 1, the Keep Inlet Formation (termed Kulshill Formation by Duchemin and Creevey, 1966) unconformably overlies the Tanmurra Formation and conformably underlies the Fossil Head Formation (termed Sugarloaf Formation by Duchemin and Creevey, 1966).

Distribution and thickness: The Keep Inlet Formation forms subcrops in an arcuate belt north of Weaber Range. Erratic blocks are locally conspicuous on tidal flats and black-soil plains. Outliers are exposed at Spirit Hill, Milligans Hills, Burt Range and possibly "The Needles". The thickest known section is 480 m in Keep River 1. The thickest outcrop section is 130 m at northeastern Mount Zimmerman, (section 2020); a similar thickness probably occurs at Spirit Hill.

Fossils and age: Plants and palynomorphs are the commonest fossils, with rare trace fossils at Milligans Hills. A single specimen of the brachiopod *Strophalosia* was recovered from a reworked calcareous sandstone block in the type locality (Glover and others 1955; Veevers and Roberts, 1968). Spores and pollen, in Keep River 1 and in mudstone from a bore 4 km northeast of the type locality, are Early Permian (Caye, 1969) and Sakmarian (Backhouse, 1981), respectively. In Pelican Island 1 and Bonaparte 1, the unit contains a Late Carboniferous (Stephanian) microflora (Kemp and others, 1977).

FACIES ANALYSIS OF THE KEEP INLET FORMATION

SHALE-DOMINATED SEQUENCE

The shale-dominated sequence consists mainly of carbonaceous and glauconitic silty shale with beds of siltstone, sandstone, and pebbly sandstone up to 30 m thick, and minor coal. It also contains erratic blocks of diverse lithology derived from outside the basin, some of which have striated facets.

The shale-dominated sequence was probably deposited in a quiet-water glaciomarine environment. Shales represent suspension deposition. Although fossils are largely absent, a marine environment is inferred by the presence of glauconite and association with the sandstone-dominated sequence, in which wave processes are evident. The abundance and large size of erratic blocks suggest they were ice-rafted rather than transported by floating vegetation. Coal and coarser sediments indicate interfingering with marine to continental environments.

SANDSTONE-DOMINATED SEQUENCE

This sequence consists of sandstone with minor conglomerate and shale. Sandstone occurs in lenticular bodies which are mostly 10–20 m thick. They interfinger with and, more strikingly, have sharp contacts with both the conglomerate and shale. Detailed facies characteristics are known only from the Burt Range (Fig. 117) and the descriptions (Table 14) are based mainly on these sections. The occurrences at Spirit Hill are poorly known, and only gross lithologies are known in the subsurface.

Conglomerates were probably deposited in high-energy fluvial or alluvial-fan environments, with minor marine deposition. Facies *Ga* was deposited as longitudinal bars, and facies *Gm* as lag or sieve deposits in channels. The large planar cross-beds (facies *Gp*) represent gravel waves and their downdip continuity suggests foreset progradation into a water body. Palaeocurrents indicate a general northwesterly palaeoslope. Dewatering pits (Fig. 118) in facies *Ga* at Milligans Hills indicate deposition on a steep slope (Postma, 1983). Interfingering with shoreface sandstone facies suggests that deposition occurred partly in beach or upper shoreface environment.

Sandstones were deposited mainly in a marine environment in the area of Burt Range–Milligans Hills and in a fluvial environment at Spirit Hill. At

TABLE 14. FACIES IN THE KEEP INLET FORMATION

Facies		*Description*
CONGLOMERATE:		
Gp	Planar cross-bedded	Beds <14 m thick, sets 1–5 m, continuous for several hundred metres; foresets 5–30 cm, alternating pebbly sandstone and conglomerate, dip 13°–21°; palaeocurrents vary, clockwise, from southwest to north-northwest
Ga	Parallel bedded	Imbrication common, palaeocurrents to west and north; rare dewatering pits.
Gm	Massive	Lens <25 m thick, channel infill (southern Mount Zimmerman, 1000 m wide x 15 m deep); minor imbrication and *Ga*; palaeocurrents to west.
SANDSTONE:		
Sh	Laminated	Fine to medium grained; beds <17 m; common steep-sided channels <2 m deep, infill of *Sm* or *St;* rare pebble lags, armoured mud balls, load casts (over shales); partly transitional with *Sl.*
Sm	Massive	Very fine to medium grained; beds <14 m and channel infill; local basal intraformational conglomerate, shale, sandstone clasts; minor *Sp*, grades upwards into *Sh* or rarely *St;* rare lenses of quartzite pebbles.
Sp	Planar cross-bedded	Fine to coarse grained, pebbly (Spirit Hill), non-pebbly (Burt Range); sets <3 m; palaeocurrents to west and north; associated with facies *Sh, Sl, Sa* at Burt Range.
St	Trough cross-bedded	Medium to coarse grained, pebbly beneath conglomerate; beds <4 m, sets 0.3–0.5 m in *Sa, Sh,* and *Sm*, palaeocurrents north to northeast.
Sa	Parallel bedded	Very fine to medium grained; beds <10 m, sets 0.1–0.5 m; local shale lens; parting lineation oriented northwest to southeast.
Sl	Low-angle cross-bedding	Medium grained, pebbly beneath conglomerate; beds <2 m or associated with *Sh;* foreset dip <6°.
Sr	Ripple cross-laminated	Fine to medium grained; beds 2–4 m; interference or symmetrical longitudinal types; northwest to southeast oriented crests (Burt Range).
SHALE:		
Fm	Massive	Beds <15 m; local dropstones and slumped sandstone blocks (Mount Septimus); rare bioturbation.
Fh	Laminated	Beds <3 m; minor ripples, flaser bedding.

Burt Range, the strong segregation of clasts between conglomerate and sandstone indicates wave reworking (Clifton, 1973). Sand deposition occurred as plane beds on a shoreface under both high-energy conditions (*Sh*) and low-energy conditions (*Sa*). Undulating bed forms possibly represent beach deposition (*Sl*). Massive sandstone (*Sm*) also represents high-energy deposition with the lack of bedding due to rapid deposition. Deep channels in facies *Sh*, filled with massive sandstones, are possibly storm or rip channels. Associated with the shoreface deposits, facies *Sp, St,* and *Sr*, represent lower energy deposition as sandwaves, sinuous dunes, and ripples, respectively. The north to northeast orientation of dunes is orthogonal to the inferred palaeoslope, suggesting they were formed by longshore currents. Sequences which grade upwards from facies *Sm* into facies *Sh* or *St* represent decreasing energy conditions, from initial high-energy rapid deposition to slower deposition, which allowed bed forms to develop.

Fluvial facies are generally more pebbly and texturally less mature than marine facies. At Spirit Hill, deposition occurred mainly as sandwaves (*Sp*) on a northwesterly palaeoslope. At Burt Range the trough cross-bedded pebbly sandstones, beneath alluvial conglomerates, may also be fluvial dunes.

Shales represent quiet-water suspension deposition and low-energy traction deposition. Dropstones can be transported by vegetation or ice, and suggest subaqueous, rather than overbank, deposition. The similarity with the glaciomarine shale-dominated sequence, suggests marine deposition.

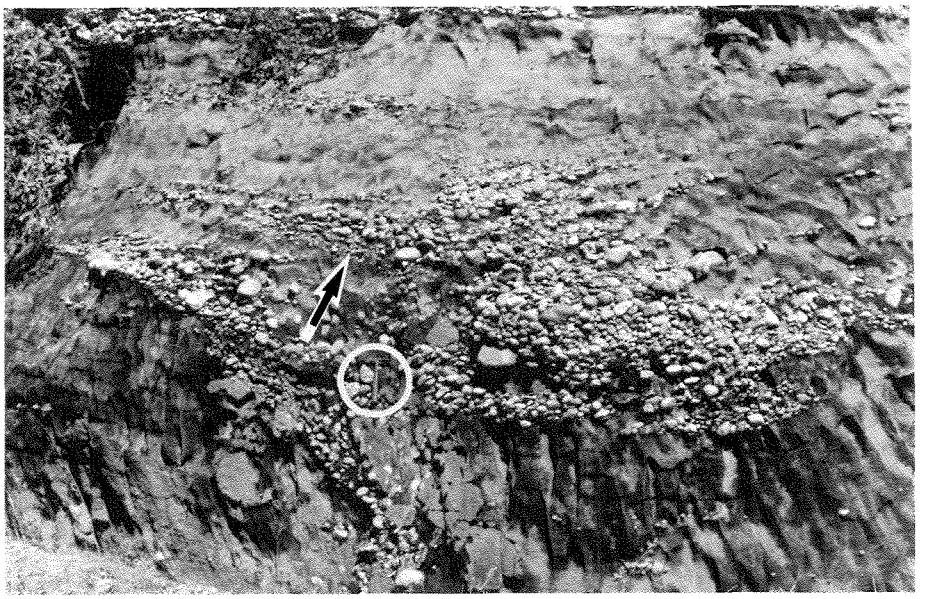

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Figure 118. Dewatering pit with conglomerate infill. The absence of disruption in the upper conglomerate beds (arrowed) indicates dewatering prior to their deposition. Keep Inlet Formation, Milligans Hills. Hammer circled.

Facies associations

Two facies associations are recognized in the sandstone-dominated sequence corresponding principally with outcrops at Burt Range and Milligans Hills (FA 1), and Spirit Hill (FA 2).

Facies association 1 (FA 1): This consists mainly of parallel-laminated and massive sandstone (*Sh* and *Sm*), parallel and planar cross-bedded conglomerate (*Ga* and *Gp*), and massive shale (*Fm*). Minor facies include *Sa, St, Sp, Sl, Gm,* and *Fh.* The facies occur in six fining-up cycles, 25–30 m thick (Fig. 117, △1-6). The base of each is accompanied by a channelled and eroded substrate and is marked by conglomerate and intraformational clasts in sandstone. Fining-up cycle 2 (△ 2, Fig. 117) has been progressively eroded northwards so that, at Milligans Hills, cycle 3 rests directly on cycle 1. Conglomerate at the bases of cycles is overlain by, or laterally transitional with, thick units mainly of facies *Sh, Sm,* or *Sa.* These in turn are overlain, or transitional with, shales (*Fm* and *Fh*). Coarsening-up sequences of sandstone occur beneath some conglomerates.

Facies association 1 is interpreted as fan deltas in which alluvial sediments were shed directly from a fault scarp into a wave-dominated shallow-marine environment (Fig. 119). Each fining-up cycle is a regressive alluvial-to-marine sequence. At the base, channels filled with lag conglomerates (*Gm*) are probably feeder channels on the fan. Facies *Gp* and *Ga* possibly formed in terminal lobes marginal to the coastline, with facies *Gp* representing delta foresets and facies *Ga* longitudinal bars on the delta topsets. The coarsening-up sequences, below these facies, represent lobe progradation. Alluvial deposition is laterally transitional with, and succeeded by, shoreface sand deposition. Deposition occurred mainly in high-energy environments (*Sh* and *Sm*) indicating that the coastline was wave dominated. The coarsening-up sequences in facies *Sh* probably reflects local shoreface progradation. Rapid deposition of facies *Sm* and dewatering pits in conglomeratic sediments suggest that deposition occurred on relatively steep slopes. Offshore marine shales cap the sequence.

Facies association 2 (FA 2): This consists mainly of facies *Sp* with minor *Gm, Ga, Gp, Sh, Sl, Sr,* and *Fm.* Both fining and thinning-up, together with coarsening-up sequences (up to 30 m thick are present. Fining-up sequences pass upwards from a conglomeratic base into facies *Sp* then facies *Sr* and *Fm.* Cross-beds in facies *Sp* vary from 3 m thick at the base to 10 m at the top. Coarsening-up sequences pass upwards from facies *Fm* and *Sh* at the base, into thick sequences of facies *Sp,* then *Ga.*

The lack of fines and abundance of planar cross-beds indicate that this association was deposited mainly in shallow braided rivers. Facies *Sh* and *Fm* may represent shoreface and offshore deposition, while the conglomerates represent alluvial deposition. Palaeocurrent directions in the braided rivers are parallel to those in alluvial sediments to the south, suggesting deposition on a

braidplain downstream from the fans. The fining-up and coarsening-up sequences represent retrogradation and progradation of fan and braided-fluvial sediments, respectively.

DEPOSITIONAL ENVIRONMENT

The Keep Inlet formation was deposited in laterally equivalant, continental, shallow-marine, and glaciomarine environments.

Deposition of the sandstone-dominated sequence was related to faulting and, in a proximal to distal sequence, occurred in alluvial-fan, braided-fluvial, shoreface, and offshore-marine environments. On a steep palaeoslope (FA 1) alluvial fans fed directly into the sea, resulting in a narrow fluvial belt and rapid facies changes (Fig. 119). Multiple cyclicity indicates that regressive sedimentation in each fan delta occurred in response to basin and hinterland uplift, followed by basin subsidence (Fig. 120) rather than by eustatic changes. Uplift initiated deposition in alluvial and shoreface environments (Fig. 120 A). Thick shoreface deposits resulted from the sedimentation rate almost keeping pace with subsidence (Fig. 120 B). As sediment input decreased with hinterland erosion, relative basin deepening occurred, resulting in deposition of increasingly offshore aspect (Fig. 120 C). Basin uplift is indicated by the erosion of marine deposits, and the juxtaposition of alluvial deposits shed from an uplifted hinterland (Fig. 120 D) on to shoreface deposits. Multiple sequences (Fig. 120 E) indicate that this tectonic cycle was repeated several times.

The predominance of braided-fluvial deposits in FA 2 suggests a broader facies belt and a lower palaeoslope than in the fan-delta model (Fig. 119). Extensive alluvial and marine deposition may have occurred but deposits are not preserved. Depositional sequences have a similar thickness to those in the fan delta, suggesting a tectonic control. Fining-up sequences may result from tectonic processes similar to those forming fan deltas, but

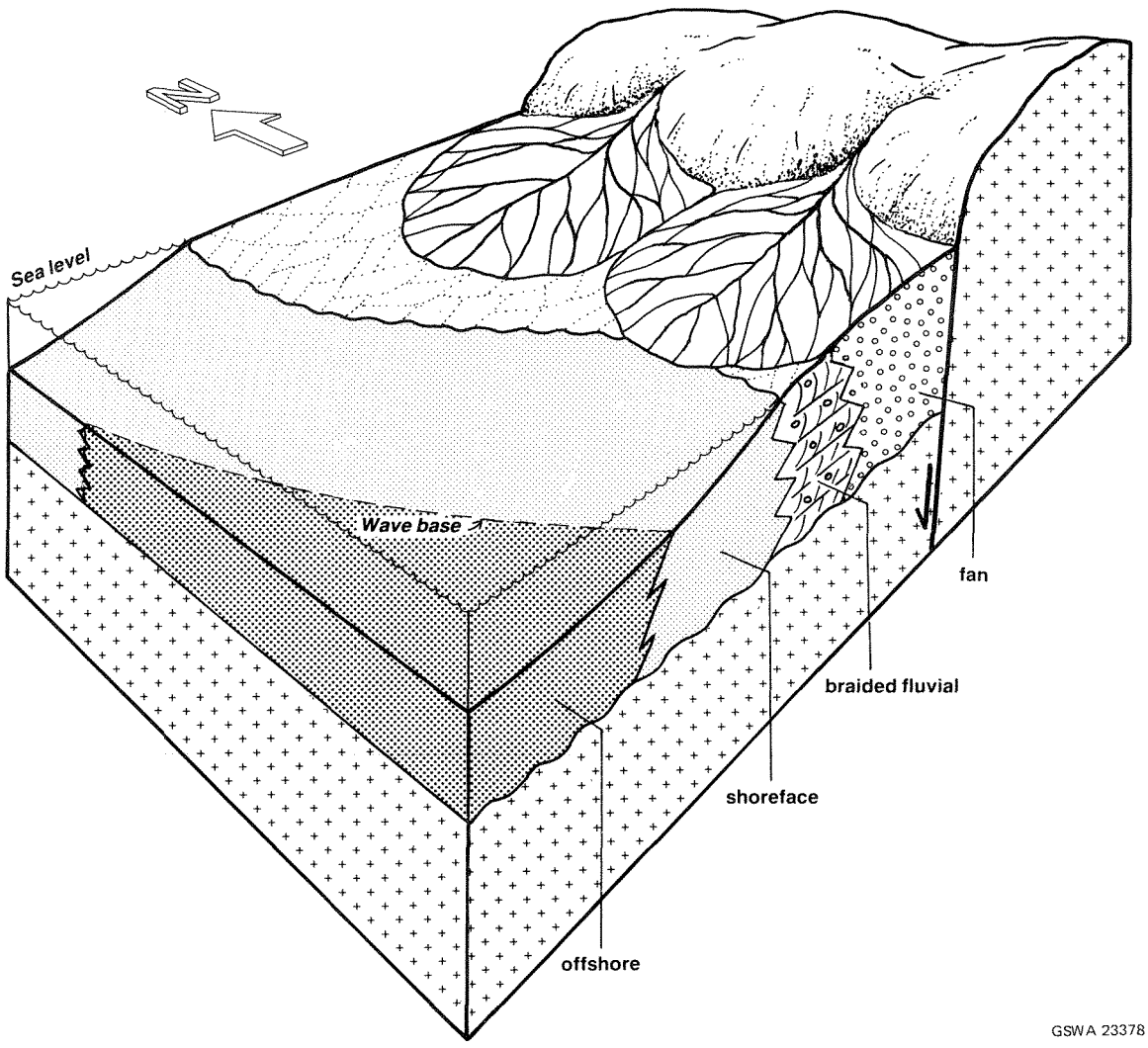

Figure 119. Depositional model for the Keep Inlet Formation.

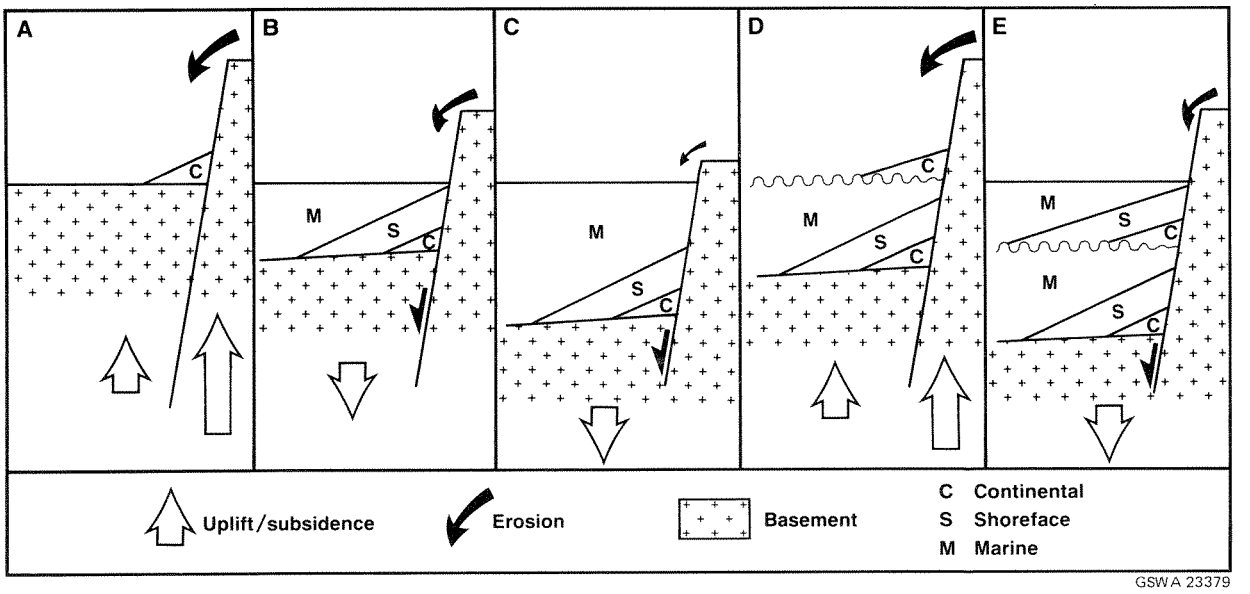

Figure 120. Tectonic and sedimentary controls of fan-delta regressive sequences in the Keep Inlet Formation.

reflect decreasing energy in a continental environment, due to the lowering of stream base levels by hinterland erosion and basin subsidence. The coarsening-up sequences may represent active sediment input without basin subsidence, causing progradation of fans over braided rivers.

Glaciomarine sedimentation of the shale-dominated sequence possibly occurred offshore from the fan deltas and braided rivers. With the cessation of faulting and decrease in clastic input, glaciomarine sedimentation occurred in a deepening basin over the entire area.

CHAPTER 8

Cainozoic of the Bonaparte and Ord Basins

INTRODUCTION

Cainozoic sediments of alluvial, eolian, residual, lacustrine, tidal and mixed origins cover much of the onshore Bonaparte and Ord Basins. In many areas these sediments lie at a number of distinct levels; the lowest level has been named the Koolpinyah Surface and the older, higher levels, the Wave Hill, Tennant Creek, and Ashburton Surfaces (Hays, 1967). The sediments are mostly superficial and, except for two Tertiary limestones in the Ord Basin, the units have not been formally named. On the maps accompanying this bulletin the superficial sediments are grouped into broad units according to their inferred origin. Definition of these units is based largely on air-photo patterns and morphology rather than lithological differences visible on the ground. So the units are primarily morphostratigraphic in the sense of Frye and Willman (1962).

In the Bonaparte Basin most of the low-lying superficial deposits lie on the Koolpinyah Surface (Hays, 1967) in the Cambridge Gulf Lowlands, and are probably post-Miocene in age (Plumb and Gemuts, 1976). In the Ord Basin, superficial deposits along the Ord River drainage system are probably equivalent in age to sediment deposited on the Koolpinyah Surface although Hays (1967) did not recognize this surface extending so far inland. Higher level superficial deposits such as the laterite, black and residual soils and lacustrine deposits lie on the Wave Hill or Tennant Creek Surfaces. These surfaces are of Early to Middle Miocene, and Late Cretaceous to Early Tertiary age, respectively, (Hays, 1967; Plumb and Gemuts, 1976) and so give a maximum age of Early Tertiary for the overlying superficial sediments. The relationship between the Tertiary surfaces recognized by Hays (1967) and the superficial sediments deposited in the Ord and Bonaparte Basins is summarized in Figure 121.

WHITE MOUNTAIN FORMATION

The White Mountain Formation was defined by Matheson and Teichert (1948) as the "White Mountain Series" and comprises the "lacustrine sediments of probable Pliocene age . . . in a low range . . . known as White Mountain". The formation, which has since been dated as Miocene based on a single species of foraminifer (Lloyd, 1968), consists of chert, siltstone, sandstone and marl. Matheson and Teichert (1948) measured two sections of 30 m and 115 m thickness through the unit, at trigonometric station J40 (Hardman, 1885) and a ridge 2 km to the southwest of J40, respectively. The latter section (at 17°16′20″S, 128°58′40″E) is here defined as the type being the thickest section through the unit.

The White Mountain Formation is also recognized (on aerial photographs) at Agate Hills, 40 km to the southwest of the type area, where it unconformably overlies the Cambrian Antrim Plateau Volcanics and Headleys Limestone. These outcrops have not been visited and reported upon since Hardman (1885) recorded some "Carboniferous" fossils in the chalcedony and flint. Hardman did not, in fact, identify the fossils as Carboniferous forms, but miscorrelated the limestone formations he encountered with the "Carboniferous Limestone" of England and Ireland. At Agate Hills the White Mountain Formation is approximately 45 m thick.

In the White Mountain Hills, the White Mountain Formation dips at up to 20° to the northeast, on the upthrown side of a small fault, and rests unconformably on the Late Cambrian Overland Sandstone. While the base of the White Mountain Formation today lies at between 200 m and 260 m ASL, Traves (1955) estimated the level of the Tertiary landscape upon which this unit was deposited at between 335 m and 360 m ASL. This height is comparable with that at Agate Hills (350 m) and with the base of the Lawford beds in the Nicholson area (335–365 m). Hays (1967) recognized this Tertiary land surface as the Wave Hill Surface. The surface probably formed by scarp retreat from the north after minor mid-Tertiary uplift (Hays, 1967). The White Mountain Formation probably had a much wider distribution across this surface prior to the Late Miocene–Early Pliocene movements, which resulted in the dissection of the Wave Hill Surface (Hays, 1967; Plumb and Gemuts, 1976).

LAWFORD BEDS

The Lawford beds were first defined by Casey and Wells (1964) as "the massive lacustrine marl and limestone, with a chalcedony capping" which crops out along Christmas Creek on MOUNT RAMSEY, MOUNT BANNERMAN and NOONKANBAH in the Canning Basin. The type section is in an unnamed tributary of Christmas Creek 15 km northeast of Bulka Hills on MOUNT BANNERMAN (Yeates and others, 1975). The unit is also recognized in the southern part of the Ord Basin along the Nicholson River (Gemuts and Smith, 1968). In this area the Lawford beds consist of up to 10 m of unfossiliferous, fine-grained, white limestone, and chalcedony, which unconformably overlies the Antrim Plateau Volcanics or conformably overlies Tertiary laterite. Along the Nicholson River the Lawford beds separate two or more horizons of Tertiary laterite

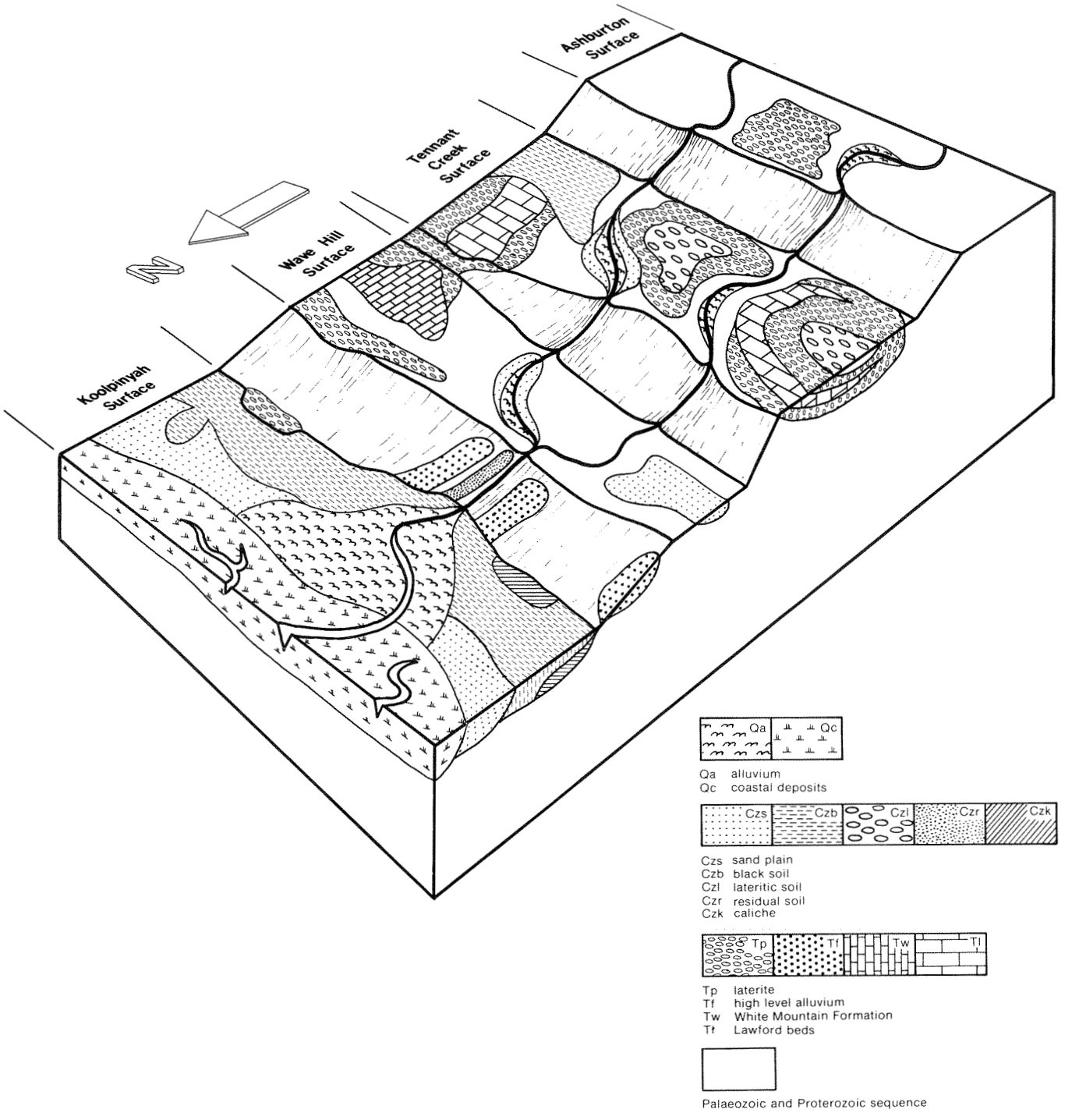

Figure 121. Summary of relationship between the four Tertiary surfaces recognized by Hays (1967) and the superficial Cainozoic sediments of the Bonaparte and Ord Basins. Not to scale.

which cannot be distinguished in the absence of the unit. The base of the unit lies between 335 to 365 m ASL, a level similar to that of the White Mountain Formation at Agate Hills. This similarity suggests that the two units overlie the same Tertiary land surface. However, Hays (1967) mapped the Tertiary land surface below the White Mountain Formation as the Wave Hill Surface and the surface in the Nicholson area, on which the Lawford beds lie, as the older Tennant Creek Surface.

The age of the Lawford beds in the type area is Cainozoic. The Holocene flora identified by Casey and Wells (1964) comes from creek beds where deposition of the unit is still taking place. In the Nicholson area the unit overlies the Tennant Creek surface of Hays (1967) and so is post-Early Tertiary in age.

HIGH-LEVEL ALLUVIUM

High-level alluvium consists of sandstone, conglomerate and siltstone perched above the modern drainage system in the area around Ord River Station. Most of these deposits are preserved as low ridges striking northwest, parallel to the creeks which cross the Nelson Shale south of the Ord River. The high-level alluvium appears to have been once quite extensive along the Ord River, in this area, and is probably related to the Tertiary history of the Ord River. Since this alluvium lies below the level of the White Mountain Limestone, it appears to post-date sediments on the Wave Hill Surface and, being dissected by modern drainage, it may pre-date the sediments on the Koolpinyah Surface in the Bonaparte Basin.

LATERITE

Pisolitic laterite up to 3 m thick overlies much of the Antrim Plateau Volcanics south of the Ord River. The laterite forms a now-dissected rolling surface with an elevation between 340 m and 420 m ASL. Along the Nicholson River the Lawford beds separate at least two horizons of laterite, but away from this area the two horizons cannot be distinguished. The laterites at the southern end of the Ord Basin are developed on the Tennant Creek Surface (Hays, 1967) and so are Late Cretaceous–Early Tertiary in age. Thin laterite, up to 0.5 m thick, and scattered ferruginous crusts are also present on Bungle Bungle Range in the Hardman Syncline at elevations between 500 m and 600 m ASL suggesting that this horizon is post-Ashburton Surface, *i.e.* pre-Late Cretaceous (Hays, 1967), or pre-Jurassic, (Plumb and Gemuts, 1976) in age.

In the Bonaparte Basin it is evident that there are two levels on which laterites developed. both levels are of limited extent and are too small to show on Plates 1 and 2. The lower level lies between 40 m and 100 m ASL at the base of hills and may be the result of reworking from the higher level, which caps hills of 200 m to 300 m ASL. Except at Mount Septimus all that remains of this higher level is a strongly ferruginized capping. Mount Septimus is the only locality in the Bonaparte Basin where a small remnant of the high-level laterite is preserved (Hays, *in* Veevers and Roberts, 1968). This high-level laterite was deposited on the now-dissected Wave Hill Surface (Hays, *in* Veevers and Roberts, 1968) of Early to Middle Miocene age (Plumb and Gemuts, 1976).

LATERITIC SOILS

Lateritic soils are developed mainly around the laterite on the Antrim Plateau Volcanics south of the Ord River. The unit formed *in situ* by degradation of the underlying laterite and so may be considered a residual soil. Lateritic soils are readily recognized on aerial photographs from the dark tones, due to the dense growth of wattle scrub.

SAND PLAINS

Sand plains in the Bonaparte and Ord Basins are largely Cainozoic residual deposits resulting from the breakdown of underlying sandstone. Where the sand plains have not been dissected by recent drainage they often show a poorly developed internal-drainage system. In both basins, structure in the underlying sandstone is visible on aerial photographs suggesting that these deposits are relatively thin. On the Carlton Shelf, bedding in the underlying Cockatoo Group is evident, whereas in the Hardman Syncline joints can be seen in the underlying Mahony Group.

The poorly developed older drainage system in the sand plains suggests relatively minor transportation of these sands by water. Locally, sand from these deposits has been blown up against the western side of hills to form mounds which are now either stabilized or are still being actively wind blown. These mounds suggest that transportation by wind may have been significant in the past by moving the sand away from the site of the parent material.

BLACK SOIL

Black soil forms extensive plains overlying shale, basalt and limestone in the Bonaparte and Ord Basins. The soil is mostly residual but may

also be transported away from its parent material, as appears to be the case with the black soil west of Ningbing Range. In the Bonaparte Basin gilgai patterns are well developed in these soils, whereas in the region to the south these patterns are not so well develped, possibly as a result of lower rainfall.

In the Bonaparte Basin, black soil is present over much of the Ord River Irrigation Area where it forms a horizon, 0.5 to 2.5 m thick, overlying red unconsolidated alluvial clay and clayey sand. In this area, at least, the black soil probably represents vegetation-worked sediment deposited by the Ord River.

RESIDUAL SOIL

Residual soil, other than black soil, is present along the western and northern sides of the Bungle Bungle Range mainly on shale of the Negri Subgroup. This soil is chiefly composed of brown, juvenile, cracking clays. The residual soil is deeply dissected with extensive sheet and gully erosion suggesting that if a mature part of the weathering profile had developed in this area, then it has since been removed by erosion.

CALICHE

Caliche consists of gravel, soil and sand cemented by calcium carbonate. It has formed at the edge of, and on, Palaeozoic limestone and shale units in the Bonaparte Basin. The most extensive deposits of caliche are in the subsurface of the Weaber Plain below the black soil where calcium carbonate, probably derived from the Ningbing and Langfield Groups, has precipitated on top of the impervious shale of the Milligans Formation.

COASTAL DEPOSITS

The extensive tidal-plain superficial deposits, of the coastal plain, are described in Coleman and Wright (1978). The oldest radiocarbon date on woody and organic material in core from these deposits is 6810 years B.P. (Thom and others, 1975) indicating a Holocene age. Within the tidal plain four main environments can be recognized: salt flats, tidal flats, tidal channels, and overbank splays.

Salt-flat deposits consist of evaporites and interbedded thin silt and mud showing desiccation cracks.

Tidal-flat sediments are predominantly fine grained and consist of bioturbated silt, mud, and sand.

Tidal-channel deposits are made up of well-sorted medium-grained sand displaying a scoured base with common bi-directional cross-bedding. The tidal-channel deposits are much burrowed by roots at the top.

Overbank splay deposits consist of alternating thin mud, silt and sand beds. Evaporites are locally present and the finer grained sediment has been bioturbated by root and animal burrowing.

Coleman and Wright (1978) indicate that the coastal deposits are probably 20 to 50 m thick and that a prograding shoreline has generated the extensive mangrove sequences. Overlying the tidal deposits, in the Westwood Creek area, are a series of vegetated beach ridges composed largely of yellow, medium-grained unconsolidated sand. Exploration drilling shows that this sand is up to 27 m thick (Ellyard, 1980). The ridges number at least twenty and they extend 2 km inland from the present shoreline. They are roughly parallel and represent successive positions of the shoreline during its advance in the Holocene.

ALLUVIUM

Alluvium consists of sand, gravel and silt, deposited along present drainage channels. Next to the Dunham and Ord Rivers and Eight Mile Creek, in the Bonaparte Basin, these deposits are extensive and often fill the floor of entire valleys. In the Ord Basin, by comparison, alluvial deposits are minor and are mostly restricted within the channels of the major creeks and rivers. This difference may be due to the Holocene landsurface being more mature in the Bonaparte Basin, allowing extensive alluvial deposits to accumulate.

In the area around the Argyle diamond mine, Meakins (1983) recognized several levels of alluvial gravels within the Smoke Creek and Limestone Creek drainage systems. In lower Smoke Creek four levels of gravels were identified: old high-level lateritized terraces approximately 8 m above the flood plain; ferruginized terraces approximately 4 m above the flood plain; flood-plain deposit; and modern channel deposits. In Limestone Creek, Meakins recognized several dissected, lateritized, piedmont fans which have been reworked into present-day creeks and flood-plain deposits.

CHAPTER 9

Palaeogeography and Basin Evolution

INTRODUCTION

Palaeozoic clastics and carbonates in the onshore Bonaparte and Ord Basins were deposited in diverse continental and shallow-marine environments, with some deep-water deposition in the Visean. The similar depositional style in both basins (to the end of the Frasnian, when the record ceases in the Ord Basin), indicates that the basins preserve only parts of a larger depositional province.

The basins have undergone three evolutionary phases:

(a) Cambrian and Ordovician volcanism and sedimentation took place in an intracratonic basin (Antrim Plateau Volcanics, Goose Hole, and Carlton Groups).

(b) Late Devonian to Late Carboniferous sedimentation (Cockatoo, Mahony, Ningbing, Langfield, and Weaber Groups) occurred in a north-northeast arm of a northwest-oriented rift system.

(c) Late Carboniferous to Permian sedimentation occurred in a north-northeast-oriented graben, possibly associated with the Halls Creek fault system.

PALAEOGEOGRAPHY

CAMBRIAN TO ORDOVICIAN

In the Early Cambrian, tholeiitic basalts of continental origin covered both the Bonaparte and Ord Basins. The basalt flows filled valleys eroded into the Proterozoic sequence, before covering a more extensive area of subdued topographic relief extending eastwards into the Wiso, Daly River and Georgina Basins. Although eruptive centres for the basalts have not been identified, it appears that the major centres of extrusion were close to, or within, the Halls Creek Mobile Zone. This is suggested by the great thickness of basalt (up to 1100 m) next to the Halls Creek Fault (Fig. 13) compared to the thinner sections to the east. The lack of identifiable eruptive centres is possibly due, at least in part, to "the burying of ..... vents by ..... superposition of thickening lava flows during the latter stages of eruption" (Bultitude, 1976).

In the Middle Cambrian a marine transgression deposited intertidal and shallow-subtidal clastics and carbonates across the Bonaparte and Ord Basins (Fig. 122). Tidal, ebb-oriented megaripples were directed to the northeast in both basins, suggesting that open-marine sediments were deposited north of the onshore Bonaparte Basin. There is no indication of the position of the coastline at this time.

A low palaeoslope is indicated by the lateral continuity and uniform lithology of early Middle Cambrian limestones in the Negri Subgroup of the Ord Basin and lithological similarity of late Middle Cambrian sandstones in the two basins. The similarity of the basal limestone in the Ord Basin (Headleys Limestone) with that in the Wiso Basin (Montejinni Limestone) suggests that the two basins were connected at least for a short period.

In the early Late Cambrian, fluvial sands were deposited in the Ord Basin while in the Bonaparte Basin a barrier-complex, of ooid and quartz sand, developed (Fig. 123). Younger Cambrian sediments are unknown in the Ord Basin, whereas in the Bonaparte Basin a transgressive marine-clastic sequence was deposited, commencing with mixed intertidal and shallow-subtidal sediments followed by open-marine sands. In the Early Ordovician, the glauconite and phosphatic fossil content of the sands increased, suggesting increased water depth.

Transportation in the Late Cambrian was predominantly to the northeast, similar to the Middle Cambrian, suggesting little change in basin configuration.

The shoreline between fluvial and barrier-complex environments was oriented northwest, perpendicular to the transport directions. The basin margin is assumed to have been a short distance to the southwest of the outcrop of fluvial sands.

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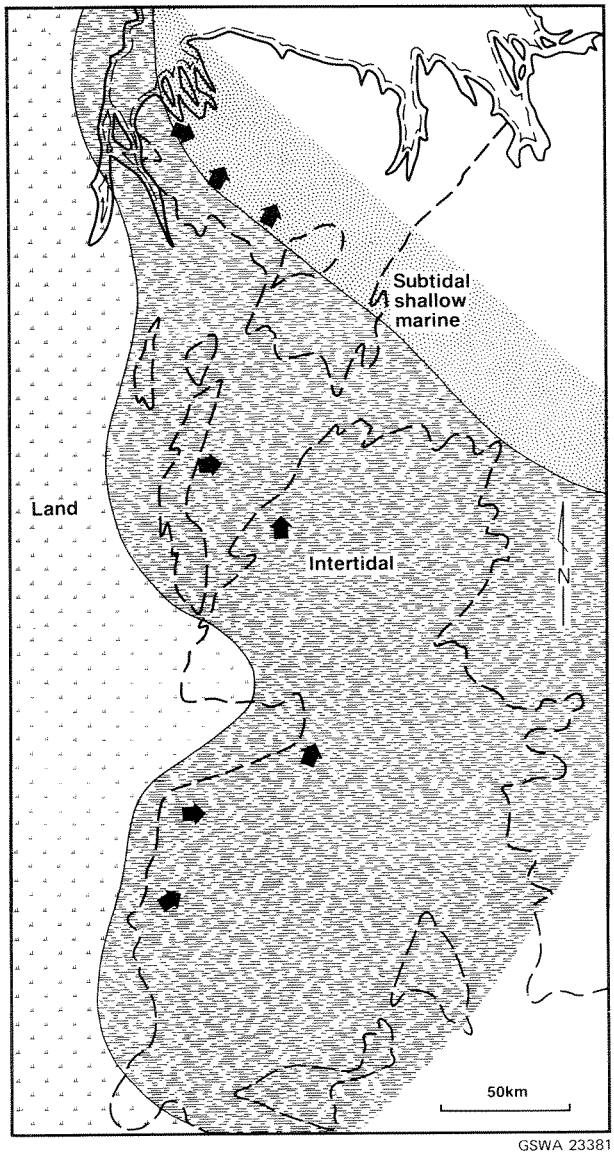

Figure 122. Middle Cambrian palaeogeography.

ORDOVICIAN TO MIDDLE DEVONIAN

Ordovician to Middle Devonian sediments are unknown in the onshore Bonaparte Basin, indicating that this was a period of non-deposition or erosion, and that it was accompanied by uplift and local faulting.

Salt encountered in Pelican Island 1 is, by analogy with the Canning Basin, probably Silurian to Early Devonian in age (Laws, 1981). Its presence in near-onshore areas may be due to subsequent lateral migration from further offshore in the Petrel sub-basin.

LATE DEVONIAN TO LATE CARBONIFEROUS

Frasnian

The upper and lower Frasnian lithostratigraphic units, recognized in the Bonaparte and Ord Basins, record two cycles of active faulting and hinterland uplift followed by denudation. Fault movements were mainly vertical, but there was possibly a dextral strike-slip component during the second phase. Deposition occurred in an alluvial-fan–fluvial–eolian–intertidal–shoreface system and a deltaic–fluvial–eolian–shallow-marine system. The alluvial system occurred in both cycles and the deltaic system occurred only in the upper part of the upper Frasnian cycle in the Bonaparte Basin. The climate was probably hot and dry.

In the Bonaparte Basin, movement along the *en echelon* Halls Creek and Revolver Creek Faults initiated sedimentation in the Frasnian (Fig. 124). Deposition occurred in alluvial fans and plains at the foot of fault scarps. Continued hinterland uplift and erosion led to the westerly progradation of proximal-fan deposits over distal-plain deposits.

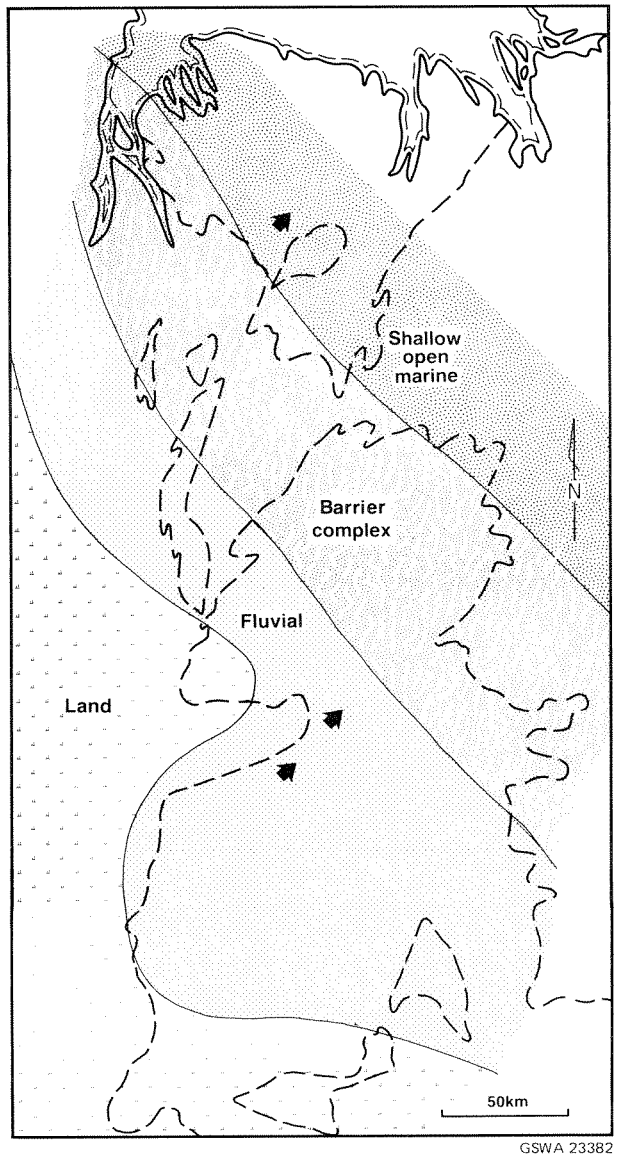

Figure 123. Late Cambrian palaeogeography.

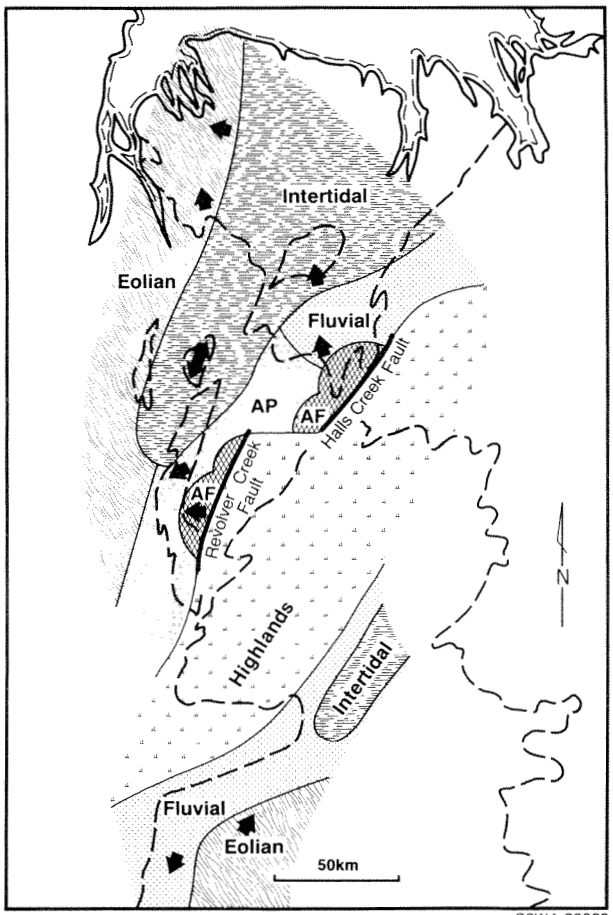

Figure 124. Early Frasnian palaeogeography. AF — alluvial fan; AP — alluvial plain.

The Revolver Creek and Halls Creek fans probably had maximum radii of 15 km and 10 km, respectively. Alluvial environments passed into braidplains, where mean flow directions were similar, or into intertidal environments. Streams on alluvial plains occupied well-defined channels, whereas streams on the braidplains occupied broad shallow channels. Tidal deposition occurred in a narrow north-northeast-oriented embayment, opening to the north. Most sedimentation occurred in subtidal areas and on intertidal flats which lacked channels. The tidal range was probably greater than 4 m. Eolian sedimentation occurred further west on the Carlton Shelf.

In the Ord Basin, sediments were derived from highlands around Osmond Range which were uplifted by movements along the Halls Creek and Revolver Creek Faults. Braided streams flowing to the south-southwest mark the initial uplift and subsequent hinterland erosion. Sediments were initially coarse grained and deposited in well-defined channels, but they quickly became finer, and deposition occurred in broad shallow rivers. East of Osmond Range, intertidal sediments suggest that another narrow marine embayment opened to the north-northeast.

In the middle of the early Frasnian cycle, tidal deposition receded seawards to the north-northeast. Movement along the Halls Creek Fault continued as did alluvial-fan deposition. Braided streams replaced alluvial environments adjacent to the Revolver Creek Fault, indicating decreased fault activity and erosion of the hinterland. Streams flowed away from the highlands across braidplains. Eolian sedimentation became more widespread and finally it blanketed most of the Bonaparte Basin. Dunes were up to tens of metres high and consisted mainly of barchanoid ridges, with some longitudinal dunes, in the Bonaparte Basin. Winds blew to the north and northeast in the Ord Basin and to the north and west in the Bonaparte Basin. Dry interdune deposits indicate an arid climate. In the Ord Basin eolian environments were succeeded firstly by an eolian sandsheet environment then shallow braided rivers.

At the end of the early Frasnian cycle, a marine transgression, possibly caused by continued basin subsidence with limited sediment input, de-

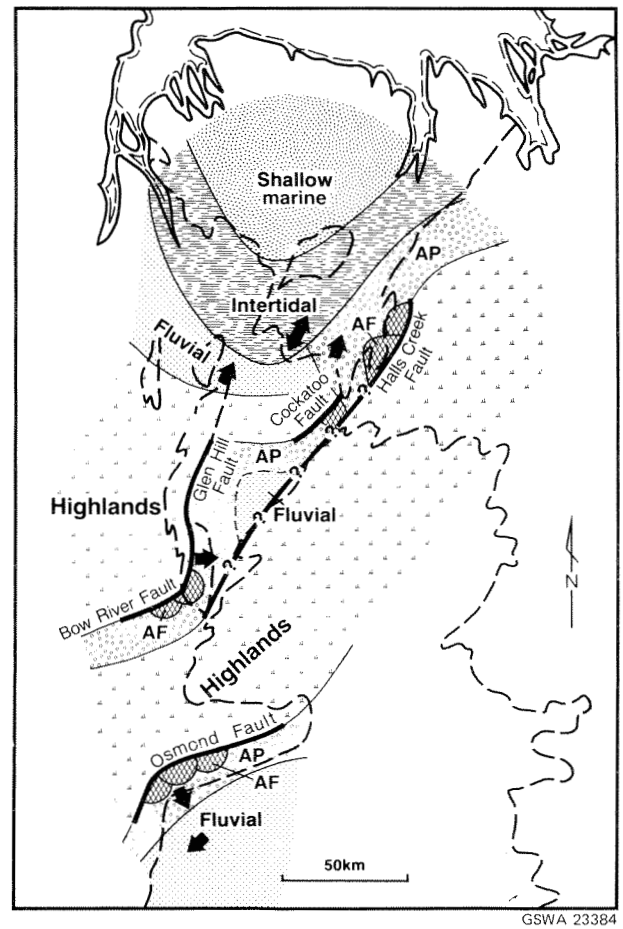

Figure 125. Middle Frasnian palaeogeography. AF — alluvial fan; AP — alluvial plain.

posited lower shoreface and offshore sediments in the Bonaparte Basin. Alluvial sedimentation probably continued along the Halls Creek Fault. The transgression did not extend into the Ord Basin where fluvial sedimentation continued throughout the Frasnian.

A new phase of tectonism initiated the second cycle of sedimentation in the late Frasnian (Fig. 125). Locally, sediments of the first cycle underwent folding at Ragged Range, also uplift and erosion around Kununurra, but elswhere sedimentation was continuous.

Faulting was widespread and a new basin developed near Galloping Creek, east of Ragged Range. Movement occurred mainly along the Halls Creek, Cockatoo, Bow River, Glenhill, and Osmond Faults. Faults may have had some dextral strike-slip motion. Two criteria used to identify strike-slip motion elsewhere occur here: patchy development of deep basins and nearby mountains (Reading, 1978); and migration of depocentres parallel to faults (Steel and Gloppen, 1980). Additionally, in the Galloping Creek area there are problems identifying faults on the present structural configuration, further suggesting strike-slip motion. In order to create basins where fans are preserved along the curved faults, right lateral (dextral) motion is required.

As before, fans were deposited at the feet of the fault scarps, and they passed distally into alluvial plains. Vertical movement on the Glenhill, Bow River and possibly the Halls Creek Faults, created a basin in the Galloping Creek area. Over 2000 m of coarse sediments in the west indicate repeated fault movements. The fining-up megasequence in the southern areas probably records the northwards shift of the depocentre, with faulting becoming more distant.

The Osmond fan records two phases of uplift then erosion, and it probably had a maximum radius of 20 km. The Cockatoo fan was probably localized within a small graben bounded on the east by the Halls Creek Fault. Further north, the Halls Creek fan probably had a radius of about 10 km, similar to that in the first cycle. The small thickness of the Cockatoo and Halls Creek fans probably indicates relatively limited vertical movement. Alluvial deposits passed distally into fluvial or intertidal deposits. In the Ord Basin, braided rivers flowed transverse to the fans in broad shallow channels.

Fluvial deposition in the Galloping Creek area was mainly by high-energy sheetfloods. To the north at Dillon Spring braided streams flowed northwards from highlands uplifted along the Bow River and Glenhill Faults. Alluvial and fluvial environments passed northwards into an intertidal environment where conditions were probably similar to those in the lower cycle. The end of this phase is marked by reduced uplift and the cessation of alluvial sedimentation.

The upper part of the late Frasnian cycle is marked by a new depositional system and lack of faulting (Fig. 126). Braided streams flowed to the north-northeast in the Bonaparte Basin and probably continued to flow to the south-southeast in the Ord Basin, suggesting highlands between. Winds blowing to the southwest formed localized fields of longitudinal dunes interspersed with fluvial deposits in the Bonaparte Basin. Evaporites accumulated in some interdunes. Fluvial sands passed northwards into a tidally influenced delta. Sands were deposited mainly in fluvial and distributary channels, and carbonates were deposited in intertidal interdistributary bays. Further offshore, low clastic input allowed pinnacle-reef development. Continued decreasing clastic input enabled more widespread reef deposition during the Famennian in the Bonaparte Basin.

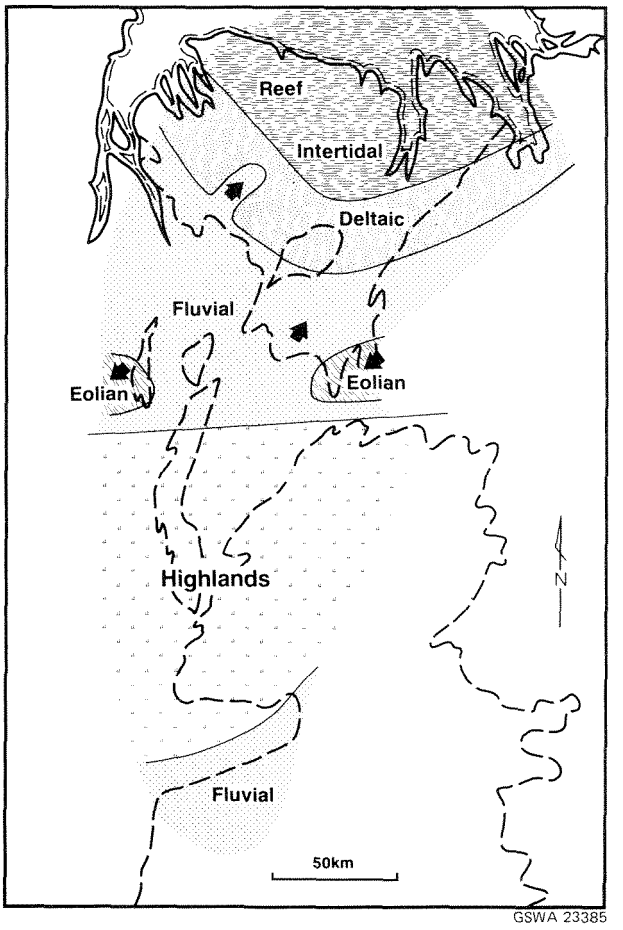

Figure 126. Late Frasnian palaeogeography.

Although the youngest preserved Palaeozoic sediments in the Ord Basin were deposited in the Frasnian, sedimentation almost certainly continued after this. Low-grade regional metamorphism of the Antrim Plateau Volcanics indicates a depth of burial of 3–4 km assuming a very high geothermal gradient of 50°C/km, or 5–6 km assuming a normal geothermal gradient of 30°C/km. At present only about 1.5 km of sediment overlies the volcanics, indicating at least a similar thickness has been eroded.

The Piccaninny Structure occurs in the thickest section of sediments in Bungle Bungle Range. Only the lower parts of this meteorite-impact structure are now preserved (Shoemaker, 1984, pers. comm.) indicating a few kilometres of overlying sediment are missing. Similarly, compaction of the sandstones in the Mahony Group, by a considerable thickness of sediment, is indicated by closely interlocked sand grains with distinct quartz overgrowths and, in some cases, sutured contacts (Young, 1986). The top of the range is a remnant of either the Late Cretaceous to Early Tertiary Ashburton Surface or the pre-Jurassic Tennant Creek Surface, indicating that the erosion occurred prior to the Early Tertiary.

Famennian

In the early Famennian (approximately do II) a reef complex was established along the edges of the Carlton and Burt Range Shelves (Fig. 127). Three distinct environments were developed: platform carbonate, marginal-slope, and basin. The platform-carbonate environment lies shorewards of the reef margin, in shallow water, and was up to 9 km across which suggests a relatively low early Famennian palaeoslope. The marginal-slope environment accumulated on slopes as steep as 40° adjacent to the carbonate platform. At the toe of the marginal-slope environment talus deposits, shale, and limestone accumulated in a basinal environment in water depths of over 200 m. Stromatolitic mounds provided some local relief in the predominantly flat-lying basinal sediments.

At the southern end of Ningbing Range and at Surprise Creek, right-angle bends in the trend of the platform margin (Fig. 92) are coincident with east-northeast photolineaments. This suggests that late Devonian topography controlled the position at which the reef margin developed, since there is no late Devonian structure coincident with these lineaments. The topographic control was probably largely determined by the palaeotopography of underlying late Frasnian deltaic lobes. South of Ningbing Range a broad embayment into the platform is postulated from the abrupt change in strike

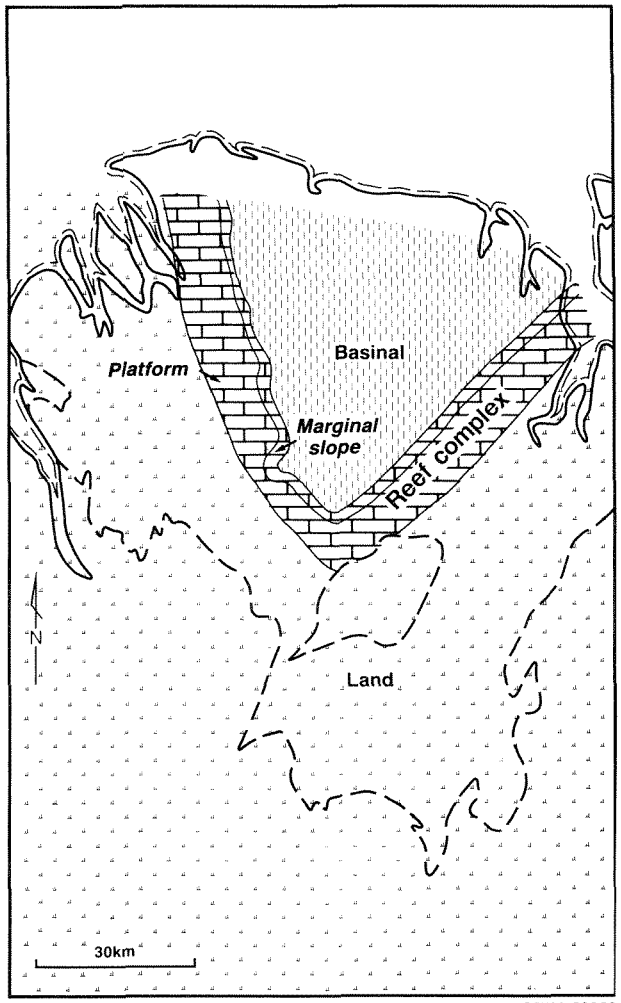

Figure 127. Early Famennian palaeogeography.

of the reef-margin (Fig. 127). The position of the platform margin at the edge of the Burt Range Shelf can only be guessed at, since the early Famennian reef complex is known only in Keep River 1 and possibly Weaber 1 in the Northern Territory.

Following the deposition of the early Famennian reef complex, a localized break in sedimentation was initiated by vertical movements on north-northwesterly oriented faults in Ningbing Range. A number of fault scarps are preserved by the subsequent drowning of the early Famennian sequence by basin and marginal-slope shale and limestone. Further south in the Jeremiah Hills, deposition of platform limestones continued into the middle Famennian (Fig. 74), whereas in the deeper parts of the basin, deposition continued throughout the Famennian. In the Ningbing Range area the reef complex advanced basinward, with middle Famennian deposition of red breccias of marginal-slope origin. A second episode of fault movement at the end of the middle Famennian, tilted the sequence, creating local unconformities

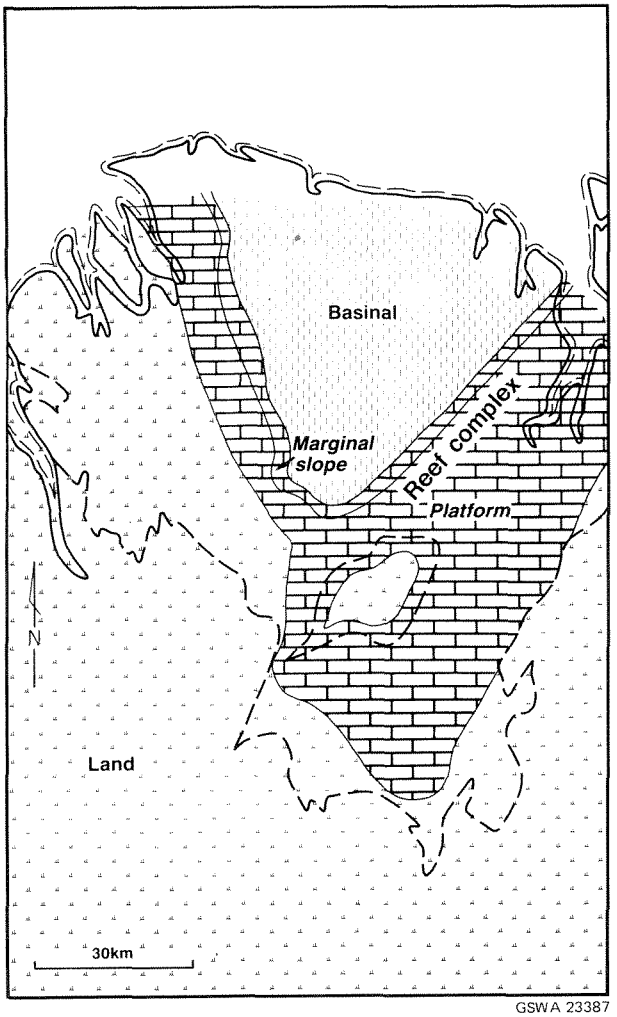

Figure 128. Late Famennian palaeogeography.

prior to deposition of the late Famennian sequence over the tilted fault blocks. The two episodes of fault movement in the middle Famennian and the resultant local unconformities are recognized only in the Ningbing Range area.

This faulting was possibly coeval with uplift of the Burt Range Shelf. Frasnian clastics were eroded from the northern margin of the Pincombe Inlier and there was non-deposition or erosion of carbonates during the early to middle Famennian (Fig. 127).

The late Famennian (do V–VI) reef-margin was re-established close to the early Famennian trend (Fig. 128).

At this time the platform extended over the Pincombe Inlier and well into the Burt Range Shelf, indicating a low palaeoslope at the basin margin.

The possibility that the Famennian reef complexes of the Canning and Bonaparte Basins were connected, around the Precambrian Kimberley Basin via the Browse Basin, was suggested by Playford (1969). This hypothesis remains unconfirmed as at least the entire Cambrian to Carboniferous sequence is missing in the four petroleum-exploration wells, which intersected basement in the Browse Basin. However, these wells (Leveque 1, Rob Roy 1, Adele Island 1 and Londonderry 1) were drilled on the Leveque and Yampi Shelves, and it is still possible that the Devonian reef complexes are present further to the west. In the offshore Bonaparte Basin the Devonian is missing from the wells which have intersected basement. The only wells to encounter Devonian sediments intersected basinal shales (Bonaparte Formation) and were located some distance from the basin margin. Pre-Permian faults with a large down-into-the-basin throw, along the southwest margin of the Bonaparte Basin, have probably displaced the Devonian to considerable depths. Thus, it seems unlikely that drilling can demonstrate the presence, or otherwise, of a Devonian reef complex in the offshore Bonaparte Basin.

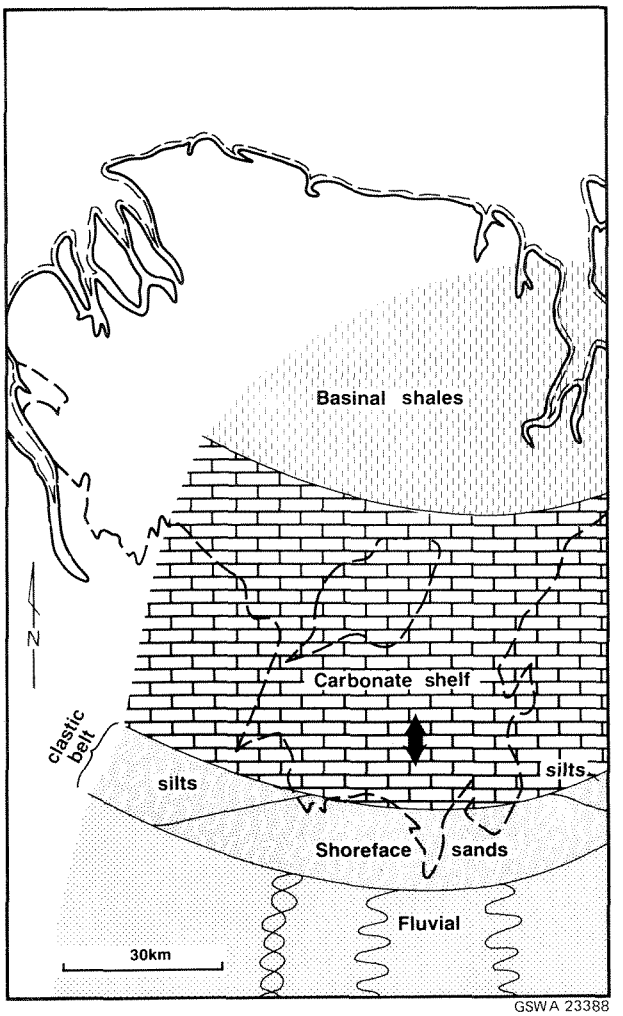

Figure 129. Early Tournaisian palaeogeography.

Tournaisian

Tournaisian deposition in the Bonaparte Basin occurred on a clastic-influenced carbonate shelf and consisted of two cycles of siliciclastic progradation over the carbonates (Fig. 129). The siliciclastics occurred shorewards of the carbonates. Tidal channels and beach deposits in both cycles indicate that the shoreline was oriented east-west in the Burt Range area. Carbonates in the lower cycle were deposited in an inner-shelf environment on a gentle seaward-sloping ramp, and siliciclastics were deposited in barrier and shoreface environments. The areal extent of these environments is poorly known; however, the carbonate belt was possibly 60 km wide. Burt Range Formation carbonates are known from as far north as Sorby Hills and Ningbing Range, but there is a change to shelf and basinal clastic deposition in Weaber 1 and Keep River 1. In southern areas the unit thins rapidly to the south of Burt Range, indicating proximity of the sandstone belt, since carbonate production is reduced in these mixing environments (Walker and others, 1983). The width of the sandstone belt is unknown. Tectonic uplift of the hinterland caused progradation of the clastics as far north as Keep River 1.

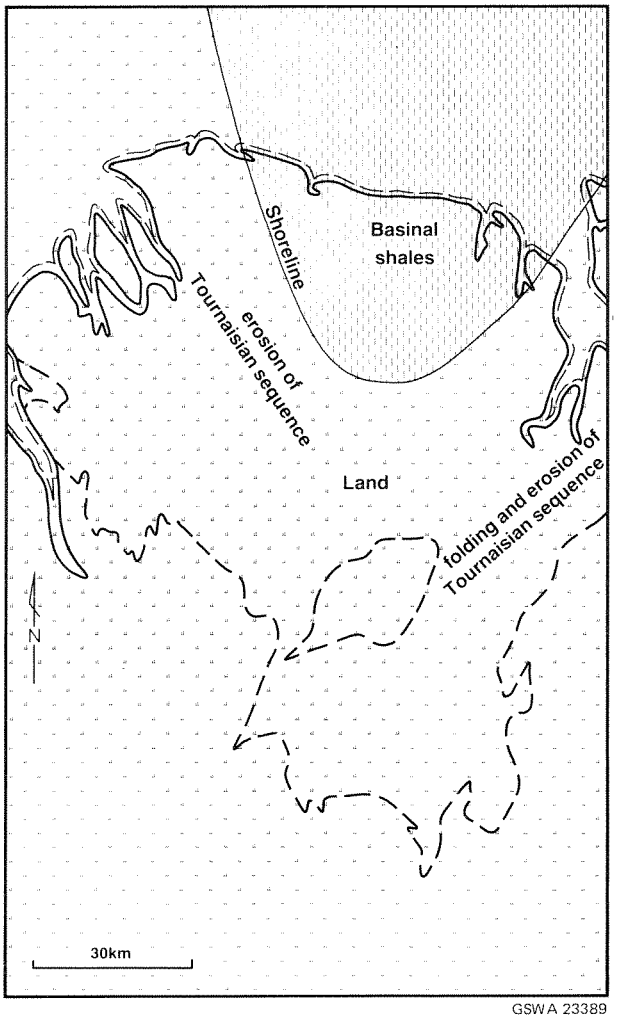

Figure 130. Late Tournaisian palaeogeography.

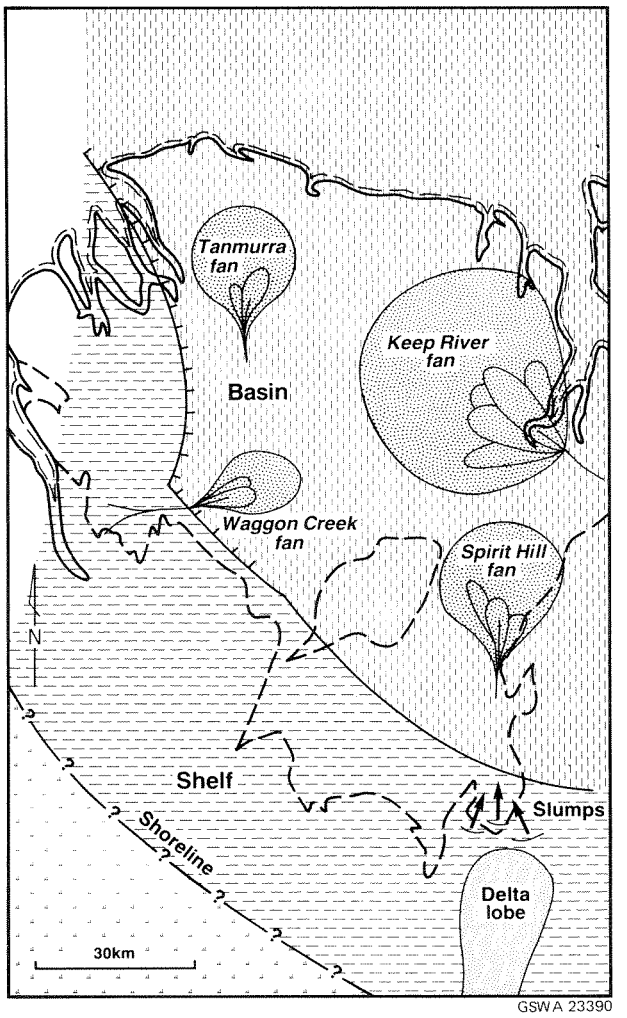

Figure 131. Early–Late Visean palaeogeography.

Carbonates in the upper cycle were deposited on a shelf with a well-defined outer margin. Siliciclastic deposition occurred in shoreface and offshore environments. The carbonate belt was possibly 40 to 50 km wide, because the Septimus Limestone is known only as far north as Sorby Hills, and to the south it thins substantially. Fine clastics were probably derived from a hinterland of low relief, and progradation was probably caused by a reduced rate of basin subsidence.

At the end of the Tournaisian a break in sedimentation is evident on both the Burt Range and Carlton Shelves, also the southern part of the Petrel Sub-basin. Folding and faulting took place on the Burt Range Shelf, while a significant phase of uplift and erosion removed most of the Tournaisian sequence from the Carlton Shelf (Fig. 130). Further north sedimentation continued uninterrupted across the Tournaisian-Visean boundary.

Visean to Westphalian

Basinal and shelf deposition began in the early Visean, and was followed by shelf and continental sedimentation in the late Visean to Westphalian. Early Visean basin deepening allowed deep-water deposition. Rapid thickening of shales east of Ningbing Range was possibly due to a north-south-oriented growth fault (Fig. 131). Submarine-fan deposition occurred in the late Visean. The Waggon Creek fan was deposited at the toe of a steep non-depositional slope formed by faulting. The fault had a north and northwest orientation and probably separated basinal and shelf environments. Cambrian and Devonian rocks, shed from the shelf, were deposited in an easterly oriented canyon.

The Tanmurra, Spirit Hill and Keep River fans were probably fed from deltas on the shelf. Sediments were derived from slumps on the delta front and transported (via numerous gullies) to be deposited on a gently inclined slope, continuous with the delta. Transport on the Tanmurra fan was to the north. The lateral extent of each fan is unknown; the largest is probably the thick Keep River fan, and the smallest the locally derived Waggon Creek fan. The shelf-to-basin relief was possibly a few hundred metres. The position of the shoreline is not known.

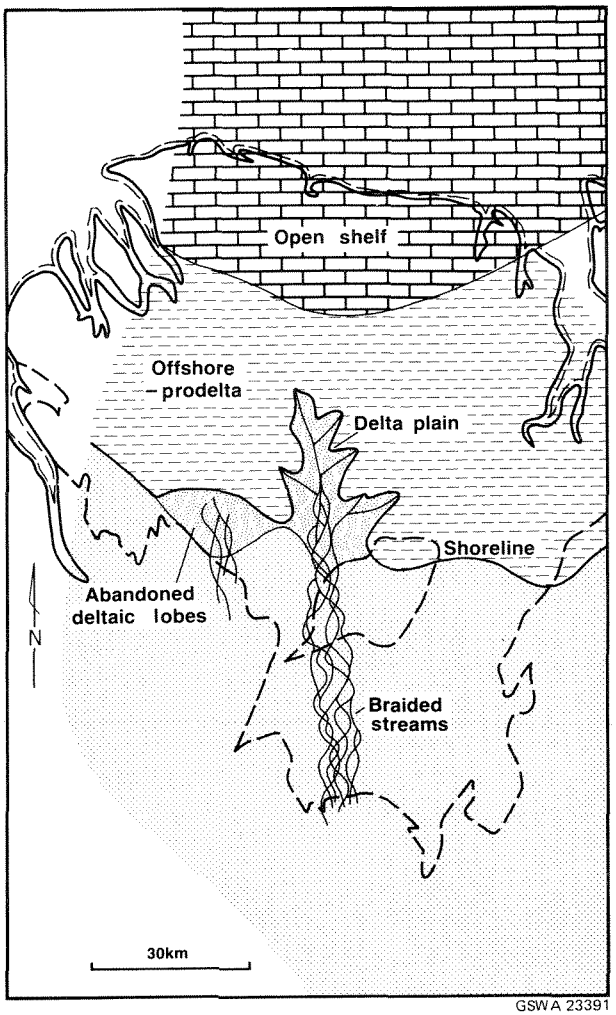

Figure 132. Late Visean–Namurian palaeogeography.

In the late Visean, Namurian, and Westphalian, basin shallowing enabled the northward progradation of shelf environments over basinal sediments (Fig. 132). Open-shelf limestones were deposited above wave base away from a delta, mainly to the north of Utting Gap and Bonaparte 1. To the south, carbonate deposition decreased and fine clastics were deposited in lower shoreface to offshore environments. Depositional environments in the fluvially dominated delta consisted of shoreface and fluvial environments, distributary mouth bars, crevasse splays, and abandoned distributary channels in the lower delta plain, also shallow braided rivers in the upper delta plain. The transport direction in the delta was generally to the north, indicating that the shore was oriented east-west. The coast probably comprised coalesced abandoned delta lobes.

LATE CARBONIFEROUS AND PERMIAN

Continental and shallow-marine sedimentation was contemporaneous with, and followed by, glaciomarine deposition. Sedimentation in response to multiple faulting occurred in alluvial-fan, fluvial, shoreface, and offshore glaciomarine environments. Six periods of basin and hinterland uplift caused the erosion of previous deposits. Decreased sediment input, with hinterland erosion and continued basin subsidence, formed regressive fan-delta and fining-upward braided-fluvial sequences. Where basin subsidence did not occur, coarsening-upward progradational fluvial to fan sequences formed. Alluvial fans formed at the foot of the Cockatoo Fault, and streams flowed to the west and north (Fig. 133). A steep northwesterly palaeoslope in the area of Burt Range–Milligans Hills caused fan deposition directly into a wave-dominated embayment, with fans possibly only a few kilometres wide. Reworking of sediment, by longshore currents flowing north and northwest, indicates that the coastline had a similar orientation. Further to the north the fans passed into a fluvial braidplain and streams flowed on a palaeoslope gently inclined to the northwest. In the embayment glaciomarine deposition became established over a wider area when faulting and clastic input decreased.

If the sand sequences of Bonaparte 1 and at "The Needles" correlate with the sequence of Burt Range–Spirit Hill, then the western side of the basin may be a mirror image of the eastern side, suggesting a gulf as little as 20 km wide.

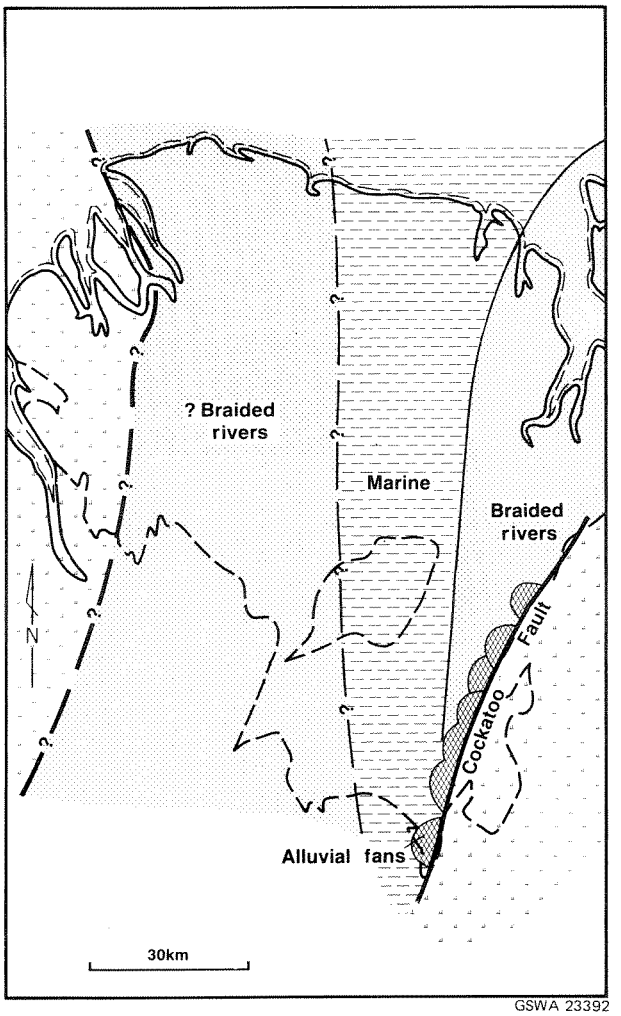

Figure 133. Late Carboniferous–Early Permian palaeogeography.

BASIN EVOLUTION

The evolution of the onshore Bonaparte and Ord Basins is geographically and tectonically linked to both the Proterozoic Halls Creek Mobile Zone and the Phanerozoic rifting events of the northwest Australian continental margin. The onshore Bonaparte and Ord Basins overlie, and are adjacent to, the north-northeast-oriented Halls Creek Mobile Zone. This major structural feature became active in the Middle Proterozoic (Plumb and Gemuts, 1976) and periodic reactivation of faults influenced Phanerozoic sedimentation.

The offshore Bonaparte Basin has undergone two phases of Phanerozoic rifting (Brown, 1980; Veevers and others, 1982). The first rifting phase is poorly known but probably occurred between the Cambrian and Early Carboniferous, resulting in the development of the northwesterly oriented Petrel Sub-basin (Fig. 134). Rifting accompanied the breakup of Gondwana and an unknown continent to the north (Brown, 1980). The second rifting phase began in the Late Carboniferous and led to Jurassic breakup and sea-floor spreading in the Timor Sea, northwest of the Petrel Sub-basin (Brown, 1980; Veevers and others, 1982).

The evolution of the onshore Bonaparte and Ord Basins with respect to the regional tectonics is summarized in Figure 135. The broad depositional styles (continental, shallow marine, deep marine) are believed to be controlled by an interplay of the depositional rate, global sea level, and basin subsidence (and tectonics). Of these, basin subsidence is the least known but can be qualitatively estimated from the sedimentation rate (Fig. 136) and global sea-level trends (Vail and others, 1977). Detailed variations in depositional style, dealt with previously in the palaeogeography section, represent smaller scale variations of these factors.

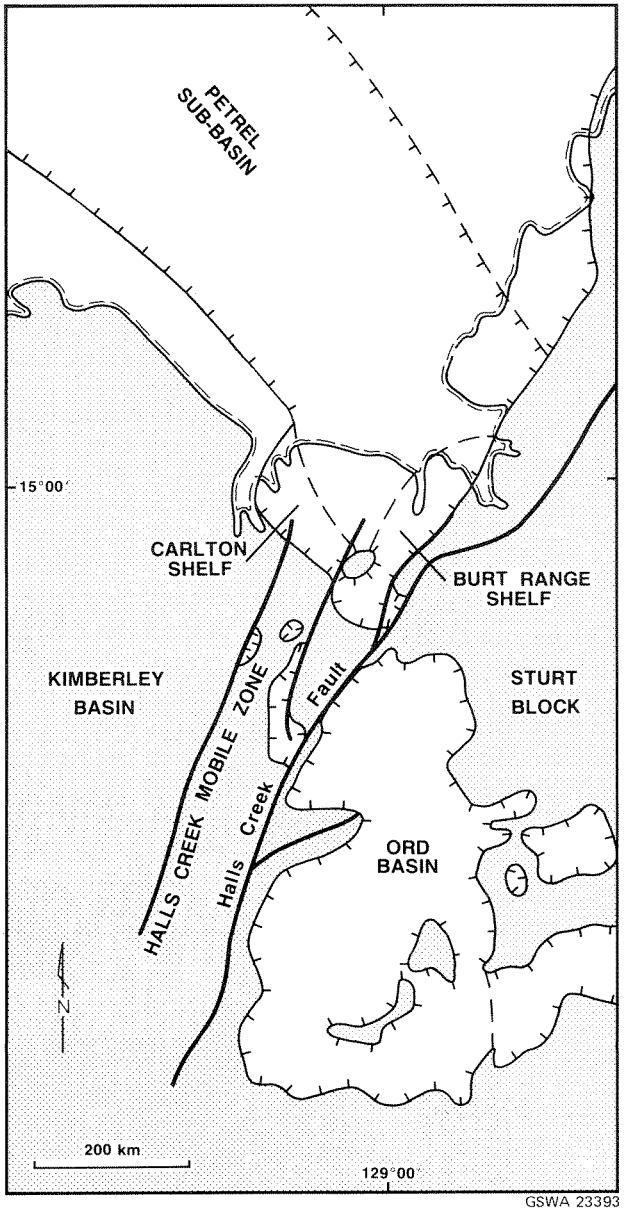

Figure 134. Regional structural setting of the Bonaparte and Ord Basins.

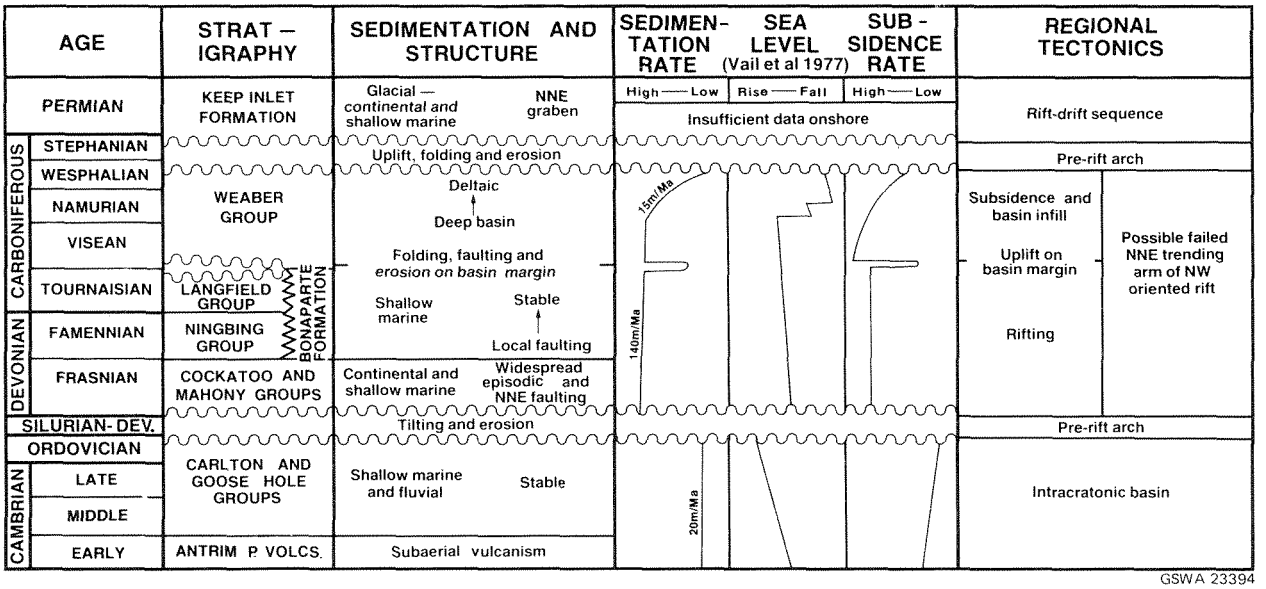

Figure 135. Evolution of the Bonaparte and Ord Basins.

The tectonic evolution of the Palaeozoic Bonaparte Basin parallels that of the onshore Canning Basin, as recognized by Brown and others (1984), with the onset of rapid subsidence being nearly synchronous in the Early Carboniferous. The timing of other events, however, is slightly different with the early Palaeozoic intracratonic phase being Ordovican to Silurian in the Canning Basin, as opposed to Cambrian to Ordovician in the Bonaparte Basin.

CAMBRIAN AND ORDOVICIAN

Cambro-Ordovician deposition occurred in an intracratonic basin rather than as an early phase of rifting, as postulated by Veevers and others (1982). Extensional tectonics enabled the extrusion of tholeiitic basalts, although feeder dykes have not been found. The depositional rate of both the volcanics and the sediments is relatively low and constant (20 m/Ma). As deposition was maintained in continental and shallow environments, the basin was probably uplifted at the same rate as the global sea-level rise.

The Ordovician to Devonian hiatus represents either erosion or non-deposition during pre-rift arching.

LATE DEVONIAN TO LATE CARBONIFEROUS

Frasnian to Westphalian deposition occurred adjacent to the Halls Creek Mobile Zone, oblique to the major rifting on a northwesterly trend in the Petrel Sub-Basin. The onshore arm of this rift is characterized by extensive tensional faulting, mainly along north-northeast and north-northwest trends, and a high rate of sedimentation (average 80 m/Ma).

The development of the Bonaparte Basin includes deposition of Frasnian continental to shallow-marine clastics and Famennian to Tournaisian marine carbonate and clastics, which together appear to be equivalent to Brown and others' (1984) "rift phase" in the Canning Basin. Subsequent Visean to Westphalian rapid subsidence and deposition of a deltaic basin-fill sequence equates with Brown and others' "subsidence and rift-infill phase". However, the late Tournaisian to early Visean basin-edge unconformity in the Bonaparte Basin cannot be explained in terms of a rifting model and probably represents localized uplift due to movements associated with the Halls Creek Mobile Zone.

The offshore Petrel Sub-basin and onshore Bonaparte Basin are similar to the Benue Trough of West Africa. The trough originated as an intracratonic rift associated with the Cretaceous separation of South America and Africa, along the other two arms of a triple junction (Grant, 1971; Adighije, 1981). It is 700 km long and has several smaller offshoots, the largest of which, the Yola Basin, is comparable in size and tectonic position to the onshore Bonaparte Basin.

Frasnian to Tournaisian

Faulting was widespread in the Frasnian, occurring mainly along north-northeast trends, parallel to the Halls Creek Fault. The Frasnian sequence contains only local evidence for dextral strike-slip fault movement in Ragged Range, contrary to Laws' (1981) suggestion that the Bonaparte Basin developed from regional sinistral motion. Local faulting and uplift in the Famennian affected the Ningbing Group, and hinterland uplift in the Tournaisian possibly caused clastic progradation of the Enga Sandstone. The sedimentation rate was initially very high (140 m/Ma) but decreased slightly, and global sea levels were slowly rising. Maintenance of continental and shallow-marine deposition throughout this period implies that the basin subsidence rate matched the sedimentation rate.

Tournaisian–Visean

The basin-edge unconformity at this time was marked by uplift and erosion on the Carlton Shelf, together with folding and faulting of the Burt Range Shelf. The sedimentation rate and rate of sea-level rise were similar to previous rates. Deposition changed from shallow to deep marine environments indicating that basin subsidence probably increased rapidly, possibly due to faulting.

Visean to Westphalian

There is limited evidence for faulting in the Visean. Growth faulting possibly occurred east of

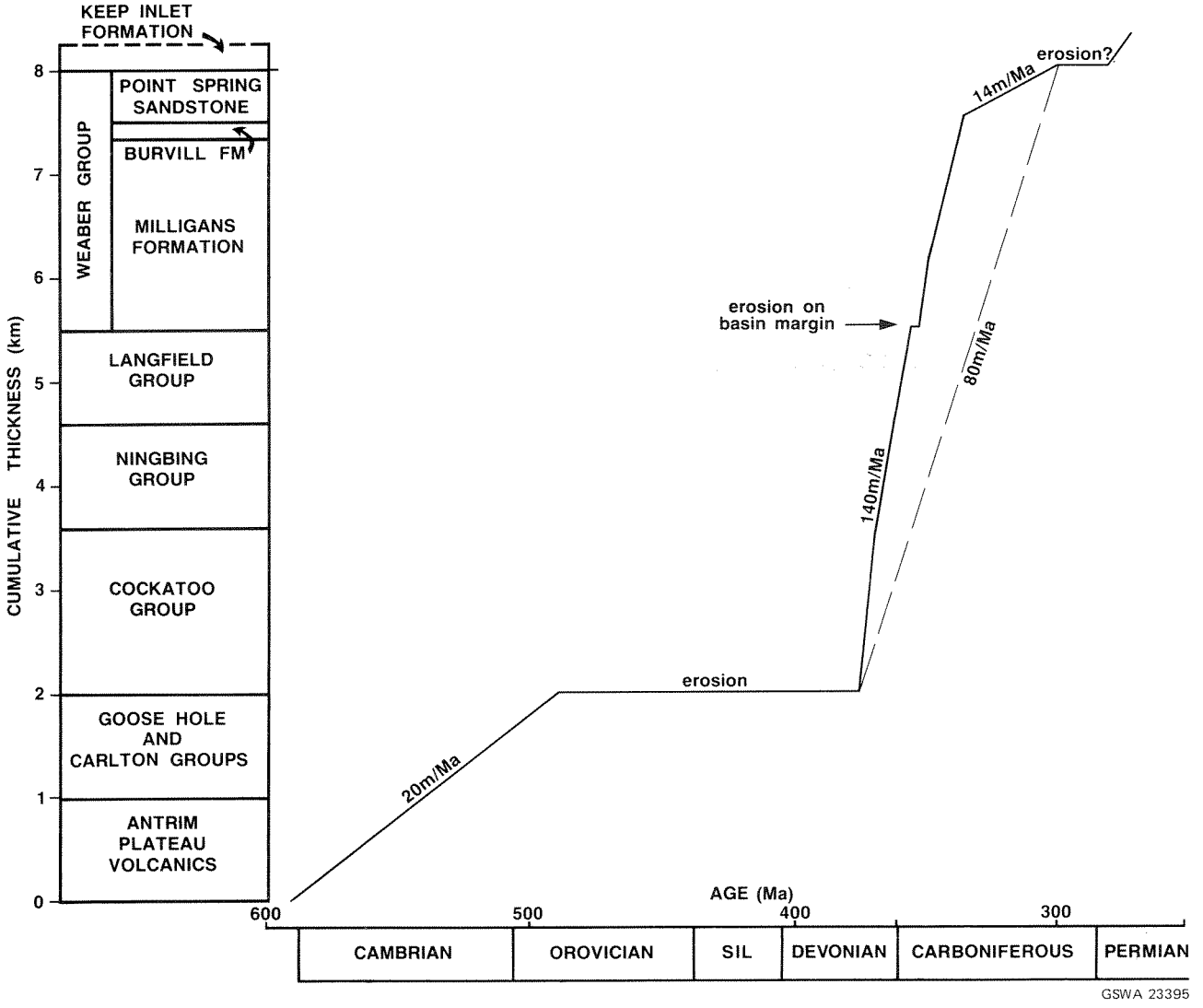

Figure 136. Sedimentation rate in the Bonaparte Basin.

Ningbing Range, and local faulting occurred west of Pretlove Hills. As the sedimentation rate remained high and the sea-level rise continued as before, the subsidence rate must have remained very high to enable deep-water deposition.

There is no evidence for faulting during the Namurian to Westphalian. The sedimentation rate slowed to as little as 15 m/Ma, and sea levels fell rapidly twice (Fig. 136). The basin shallowed and deltaic sands prograded over deep-water deposits, indicating that the subsidence rate also decreased.

LATE CARBONIFEROUS TO EARLY PERMIAN

Stephanian to Early Permian shallow-marine and continental sedimentation probably occurred in a graben subparallel to the Halls Creek fault system. Deposition was episodic in response to several periods of faulting, but there is insufficient information from onshore areas to estimate sedimentation and subsidence rates. The Westphalian-Stephanian hiatus was accompanied by uplift and erosion and folding, and may represent pre-rift arching.

CHAPTER 10

Economic Geology

INTRODUCTION

Reviews of the economic geology of the Bonaparte and Ord Basins have appeared in most stratigraphic studies of the area (e.g. Matheson and Teichert, 1948; Veevers and Roberts, 1968). Specific studies of the mineral and petroleum potential of the basins are largely in unpublished company reports; information from these reports is incorporated in this review.

BASE METALS

LEAD AND ZINC

In the Bonaparte Basin extensive exploration for carbonate-hosted Pb-Zn mineralization has been undertaken since the early 1970s, in the Ningbing Group and Burt Range Formation. The Burt Range Formation has been explored principally in the Sorby Hills area where a significant resource has been discovered. Descriptions of the prospect are given by Rowley and Lee (1986) and Ringrose (in press); the following summary is from these.

Sorby Hills lie at the northeastern tip of Pincombe Range, about 55 km by road from Kununurra. Mineralization was discovered in 1971 and extensive drilling has delineated an inferred 16.25 Mt of 5.3% Pb, 0.6% Zn, and 56 g/t Ag, at a cut-off grade of 2.5% for lead plus zinc, and a 3.0 m minumum thickness (Rowley and Lee, 1986). Mineralization occurs in several irregular-shaped discrete bodies, a few kilometres to the north and east of Sorby Hills and between 40 m and 180 m below the black-soil plain. The bodies are up to 700 m x 500 m x 10 m in size, and occur along two north-northwest and north-northeast-oriented zones. The mineralization is stratabound, occurring mainly in a lenticular intraformational breccia at the base of the Knox Siltstone Member (Rowley and Lee, 1986). Ore minerals are mainly galena, sphalerite, pyrite, marcasite, and chalcopyrite. Pervasive dolomitization preceded local silicification and sulphide precipitation and a "mixing" genetic model has been proposed for the mineralization. In this model, metal-enriched basinal brines are precipitated as sulphides, after mixing with locally derived reduced-sulphur solutions, at relatively shallow depths. An exploratory decline was abandoned in 1979 due to excessive water inflow, and the prospect was still being evaluated in 1986. Minor mineralization occurs elsewhere in the Burt Range Formation and in the Buttons Formation.

The Ningbing Group has been explored in the Jeremiah Hills and Ningbing Range, particularly around a small zinc gossan at Knob Peak. No significant mineralization has been found.

In the Ord Basin, minor lead occurrences in the Goose Hole Group were first noted by Hardman (1885) and have been described by Simpson (1951). Lead occurrences in Proterozoic rocks are described by Blockley (1971).

COPPER

Minor copper occurrences in the Bonaparte and Ord Basins are described by Marston (1979).

COAL

Two formations in the Bonaparte Basin contain environments prospective for coal—the Permian Keep Inlet Formation and the Point Spring Sandstone—although exploration to date has found coal only in the former unit.

In the Keep Inlet Formation, both sand-dominated and overlying shale-dominated units contain coal in the subsurface. The thickest coal intersections are in Keep River 1 and the Skull Creek area. The shale-dominated sequence contains coal beds 1.5 to 3 m thick, in Keep River 1 (Caye, 1969). Elsewhere the shale is carbonaceous with variable amounts of fine coaly material. In the Skull Creek area the sand-dominated sequence contains several coal lenses from 0.2 to 0.5 m thick (McBain, 1982). The sandstone appears rich in coal stringers and partings, between Attack Spring

and Calf Spring (Williams, 1982). Traces of coal also occur in Keep River 1 and Skull 1 in the sand-dominated sequence.

The Keep Inlet Formation underlies over 1500 km^2 in Western Australia and has been tested by 21 reconnaissance coal bores (Williams, 1982; McBain, 1982). In view of the widespread distribution of these bores and the lack of core drilling (with geophysical downhole logging), it is considered that the coal potential has been inadequately tested.

PETROLEUM POTENTIAL

The late Palaeozoic sequence in the Bonaparte Basin is considered to be prospective for petroleum (Fig. 137). By comparison, the early Palaeozoic sequence in the Bonaparte and Ord Basins and the late Palaeozoic sequence in the Ord Basin are not considered to be prospective, since the former is overmature (having been buried by more than 3.5 km of overburden) and the latter has no seal.

Hydrocarbon shows and source potential

In the onshore Bonaparte Basin, gas has been obtained from drill-stem tests in Bonaparte 2 and Keep River 1. In Bonaparte 2 gas flowed at 44 000 m^3 per day from a sand in the Milligans Formation, between 1437 m and 1440 m. In Keep River 1 a gas flow of 85 000 m^3 per day reducing to 5700 m^3 per day after eight hours was recorded over the interval 2583 m to 3353 m in the Bonaparte Formation, Enga Sandstone and Milligans Formation (Fig. 108). Both gas flows were considered uncommercial. Small oil shows have also been reported from the Milligans Formation in Spirit Hill 1. However, it was the numerous shows of biodegraded bitumen in shallow mineral-exploration drill holes around the edge of the Bonaparte Basin which renewed interest in the petroleum potential of this basin (Laws, 1981; Playford, P. E., 1982). These shows are primarily from the Ningbing and Langfield Groups and have chromatographic signatures similar to those from traces of oil in shale from the Milligans Formation (R. Alexander, written comm., 1980), suggesting the Milligans Formation as the source. By comparison McKirdy (*in* Garside, 1982) indicates that the small undegraded oil show in the Kamilili Formation in Ningbing 1 "probably was derived from algal/bacterial kerogen preserved in intra-formational organic-rich micrites". This suggests that the Ningbing Group has some source potential. Source-rock analyses of the Milligans Formation, from shallow drill holes, indicate moderate to high levels of oil-prone organic matter, whereas shales from the Milligans and Bonaparte Formations sampled in the deeper oil-exploration wells are generally gas-prone (Laws, 1981).

Maturation

Vitrinite reflectance data from Ningbing 1 and Bonaparte 2 suggest that the top of the oil window is close to the present ground level. Thus, the low maturity of the oil encountered in mineral-exploration drill holes around the basin margin (Laws, 1981) suggests that this oil has not migrated far. The base of the oil window lies somewhat below 2000 m suggesting that the lower parts of the Cockatoo Group and all of the Carlton Group are post-mature and unlikely to host hydrocarbon accumulations.

Reservoirs

Known reservoirs are restricted to the following units: thin sands in the Bonaparte and Milligans Formations; sands in the Langfield, Weaber and Cockatoo Groups; and carbonates of the Ningbing and Langfield Groups. In Bonaparte 2, poor to fair porosities and permeabilities were reported for thin sands in the Milligans Formation with one core analysis at 1387 m giving a porosity of 16% and a permeability of 16 mD (Le Blanc, 1965). By comparison very good porosities and permeabilities, up to 25% and 500 mD, respectively, have been demonstrated for sands in this unit from mineral-exploration drill holes (Laws, 1981). Little subsurface information is available on the reservoir characteristics of sands in the Weaber, Langfield and Cockatoo Groups. However, inspection of outcrop indicates that they have excellent characteristics.

The carbonates of the Ningbing Group are considered to have the main reservoir potential in the onshore Bonaparte Basin (Laws, 1981). However, in the petroleum-exploration wells which intersected this unit (Keep River 1, Ningbing 1 and Weaber 1), porosities and permeabilities have been negligible. By comparison, poor to good porosities have been measured in cores from shallow mineral-exploration drill holes with an average of around 7% (Laws, 1981). This porosity is largely due to mesogenetic dolomitization which probably took place (in the Late Carboniferous) after the deposition of the overlying Lower Carboniferous Milligans Formation. Carbonates in the Langfield Group probably have similar reservoir characteristics to the Ningbing Group.

Seal

Shale in the Milligans Formation provides the only regional seal in the onshore Bonaparte Basin. Shale in the basinal facies of the Ningbing Group

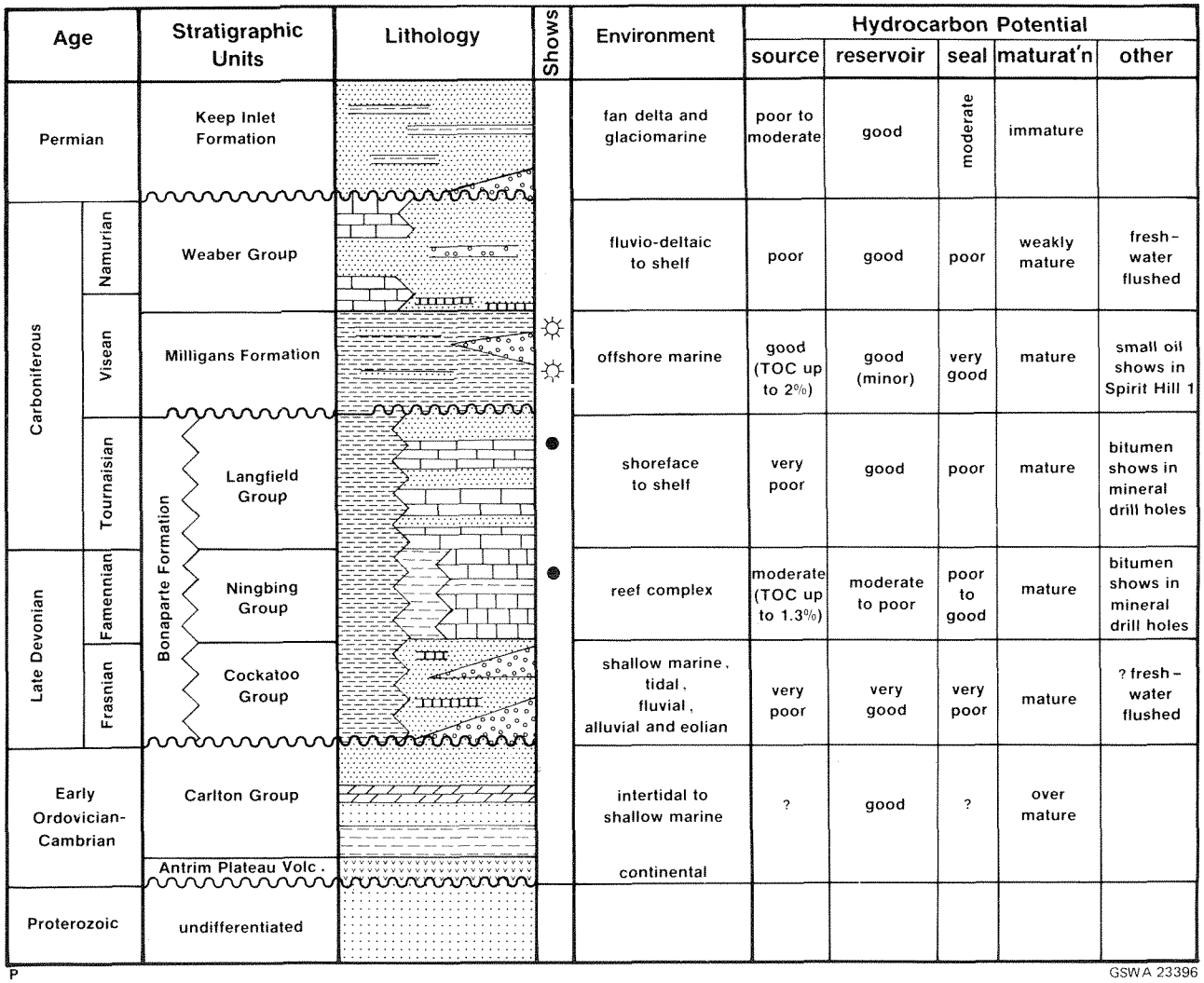

Figure 137. Summary of the stratigraphy and petroleum potential of the onshore Bonaparte Basin. The comments for the Milligans Formation also apply to the Bonaparte Formation. Stratigraphic column not to scale.

(Kamilili Formation) probably provides a more localized seal, in a narrow belt along the eastern side of Ningbing Range and possibly north of the Jeremiah Hills.

Play concepts

Both structural and stratigraphic plays are identified in the Bonaparte Basin. In order of decreasing prospectivity these plays are:

(a) sandstone in the Bonaparte and Milligans Formations;

(b) drowned fault blocks and stromatolite reefs in the Ningbing Group;

(c) sandstone and carbonate in the Langfield Group;

(d) sandstone and carbonate in the Weaber Group; and

(e) sandstone in the Cockatoo Group.

To date the quality of seismic lines in the onshore Bonaparte Basin has been poor, possibly due to poor coupling in the dry superficial sands, and it does not allow the plays (suggested above) to be differentiated. In particular it is not possible to distinguish the Langfield Group from the Ningbing Group on the presently available seismic lines, nor is it possible to recognize structure within these two units.

In the Bonaparte and Milligans Formations, thin sands have produced moderate flows of gas. These sands may form broad anticlines, or be both laterally and vertically enclosed by the surrounding shales to form a stratigraphic trap. The areal extent of these sands may be some tens of kilometres, thus allowing the possibility of relatively large structures.

In outcrops of the Ningbing Group, a number of tilted fault blocks, drowned by basinal shale and limestone, are evident (Fig. 80 and Plate 3, section

EE'). If present in the subsurface, such structures would provide excellent prospects depending on the porosity of the carbonate below the basin facies. However, the size of these structures in outcrop is somewhat small and the Ningbing Group has a distribution restricted to a narrow belt along the edge of the Carlton and Burt Range Shelves. The other play in the Ningbing Group is the stromatolite reef similar to that intersected in Ningbing 1. This reef is visible on the seismic lines as a bulge at the top of the Ningbing Group (Fig. 137) but it proved to be very tight.

Sandstone and carbonate in the Langfield Group have been intersected in Keep River 1, Weaber 1, and Spirit Hill 1 in the Northern Territory. As with the Ningbing Group, the Langfield Group is restricted to the Carlton and Burt Range Shelves. The Langfield Group has, however, been removed by erosion over much of the Carlton Shelf. Prospects in this unit are restricted to structural and stratigraphic traps due to drape over the northeasterly extension of the Pincombe Inlier and to interfingering with the Bonaparte Formation. The petroleum potential of the group is considered to be low, because the only hydrocarbon shows encountered in this unit were the gas show in Keep River 1 and numerous bitumen occurrences in shallow mineral-exploration drill holes along the basin margin.

Sandstone and carbonate in the Weaber Group, lying stratigraphically above the Milligans Formation, have been fresh-water flushed in the onshore wells drilled to date (Laws, 1981) and so have a low hydrocarbon potential. Within this group small hydrocarbon accumulations may still be present in distributary mouth bars, if isolated by prodelta or interdistributary-bay shales.

Sandstone in the Cockatoo Group, while having excellent reservoir characteristics, has a low petroleum potential since there is only a narrow zone (between outcrop and a facies change into basinal shale) in which suitable cap rocks such as shale in the Ningbing Group are present. Possibly, small pinnacle reefs (*e.g.* Westwood Member) are present in the northwestern part of the basin, but resolution of such features below the Ningbing Group is not possible with the presently available seismic data. The highly porous nature of the Cockatoo Group in outcrop suggests that this unit may be fresh-water flushed down dip from the outcrop belt, thus, further downgrading its hydrocarbon potential. In Ningbing 1, this unit was 100% water saturated except for a small zone which yielded 2.6% residual oil.

DIAMONDS

Exploration for diamonds in the east Kimberley commenced in the 1970s but did not include the Bonaparte and Ord Basins until the late 1970s. The first diamonds were found in gravel samples from Smoke Creek in August 1979 by the Ashton Joint Venture. This led to the discovery of the Argyle Pipe (AK1) in October 1979. Alluvial mining commenced in January 1983 and has produced some 17 428 192 carats to the end of September 1985. Mining of the pipe commenced in December 1985 and produced 15 679 197 carats to the end of the financial year. An annual production of 25 000 000 carats is envisaged. The following summary of the Argyle diamond deposits is from Jaques and others (1986).

The Argyle Pipe lies immediately south of the Ragged Range Outlier and west of the Halls Creek Fault. The lamproitic pipe is dated at between 1048 Ma and 1153 Ma and is intruded into sediments of the Carr Boyd Group, which are only marginally older.

Erosion of diamonds from the Argyle Pipe has given rise to the adjacent alluvial diamond deposits of Smoke and Limestone Creeks. At Smoke Creek, the diamonds are found in gravels, both within the modern drainage channel (and associated flood plain) and within nearby higher level gravel terraces. At Limestone Creek, the deposits again consist of gravels within the modern drainage channel plus an older duricrusted alluvial fan.

The alluvial deposits at both creeks have been rapidly deposited during flash-flood conditions and have not been upgraded by the reworking and chemical weathering that characterizes many tropical alluvial diamond deposits. As a result, the grades of the deposits in proximity to the pipe are similar to that of the Argyle Pipe, *i.e.* reserve figures range from 3.0 to 4.6 ct/t compared to the approximate overall grade of 5 ct/t for the pipe. The quality of diamonds in the alluvials is somewhat higher than that of the pipe diamonds through elimination of some of the more cracked, etched, and friable stones, by wear and tear during transportation. The nominal value of alluvial stones in 1985 was A$9.30 per carat compared to A$8.30 for the pipe stones in June 1986.

Further downstream from Argyle, the grades of alluvials steadily fall away because of dilution from non-diamond-bearing tributary streams. Grades of less than 1 ct/t are the norm at the lower end of Smoke and Limestone Creeks.

Below the confluences of Smoke Creek and Limestone Creek with Lake Argyle, occasional diamonds have been recorded from Ord River gravels as far downstream as the Ord River Dam and Buttons Gap at 80 km and 150 km downstream from the Argyle Pipe, respectively.

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REFERENCES

ADIGHIJE, C. I., 1981, A gravity interpretation of the Benue Trough, Nigeria: Tectonophysics, v. 79, p. 109–128.

AHLBRANDT, T. S., and FRYBERGER, S. G., 1982, Introduction to eolian deposits, *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Am. Assoc. Petroleum Geol., Mem. 31, p. 11–47.

AHMAT, A. L., 1984, Metamorphism and possible depths of burial of the Antrim Plateau Volcanics Ord Basin: West. Australia Geol. Survey, Petrological Report 1352 (unpublished).

ARCO AUSTRALIA LIMITED, 1972, Pelican Island 1 well completion report (unpublished).

BACKHOUSE, J., 1981, A Permian palynological assemblage from the Bonaparte Gulf: West. Australia Geol. Survey, Palaeontology Report 18/81 (unpublished).

BARTLETT, W. M., 1983, Western Australian Year Book: Australian Bureau of Statistics, Perth.

BASAN, P. B., 1978, Introduction, *in* Trace fossil concepts, *edited by* P. B. BASAN: Soc. Econ. Paleontol. Mineral., Short Course No. 5, p. 1–10.

BEARD, J. S., 1979, Vegetation survey of Western Australia, Kimberley 1:1 000 000 Vegetation Series, explanatory notes to Sheet 1. The vegetation of the Kimberley area: Univ. West. Australia Press, 118 p.

BEERE, G. M., 1983, The Piccaninny structure – a cryptoexplosive feature in the Ord Basin, East Kimberley: West. Australia Geol. Survey, Record 1983/6.

BEERE, G. M. 1984, The Waggon Creek Formation – an early Carboniferous submarine fan deposit in the Bonaparte Gulf Basin: West. Australia Geol. Survey, Report 12, p. 7–14.

BEERE, G. M., and MORY, A. J., 1986, Revised stratigraphic nomenclature for the onshore Bonaparte and Ord Basins, Western Australia: West. Australia Geol. Survey, Record 1986/5.

BLATCHFORD, T., 1927, The geology of portions of the Kimberley Division, with special reference to the Fitzroy Basin and the possibilities of the occurrence of mineral oil: West. Australia Geol. Survey, Bull. 93.

BLOCKLEY, J. G., 1971, The lead, zinc, and silver deposits of Western Australia: West. Australia Geol. Survey, Mineral Resources Bull. 9.

BRADY, T. J., JAUNCEY, W., and STEIN, C., 1966, The geology of the Bonaparte Gulf Basin: APEA Jour. p. 7–11.

BROWN, C. M., 1980, Bonaparte Gulf Basin: ESCAP atlas of stratigraphy II, Stratigraphic correlation between sedimentary basins of the ESCAP region, v. 7, pt. 5: United Nations, New York, p. 42–51.

BROWN, S. A., BOSERIO, I. M., JACKSON, K. S., and SPENSE, K. W., 1984, The geological evolution of the Canning Basin – implications for petroleum exploration, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth, 1984, Proceedings, p. 85–96.

BULTITUDE, R. J., 1976, Flood basalts of probable Early Cambrian age in northern Australia, *in* Volcanism in Australia, *edited by* R. W. JOHNSON: Elsevier, Amsterdam, p. 1–20.

CANT, D. J., 1982, Fluvial facies models and their application: *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Am. Assoc. Petroleum Geol., Mem. 31, p. 115–137.

CASEY, J. N., and WELLS, A. T., 1964, The geology of the north-east Canning Basin, Western Australia: Australia BMR, Rept 49.

CAYE, J. P., 1968, The Timor Sea–Sahul Shelf area: APEA Jour., v. 8, pt. 2, p. 35–41.

CAYE, J. P., 1969, Keep River No. 1 well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

CHOQUETTE, P. W., and PRAY, L. C., 1970, Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates: Am. Assoc. Petroleum Geol., Bull. v. 54, No. 2, p. 207–250.

CLIFTON, H. E., 1973, Pebble segregation and bed lenticularity in wave-worked versus alluvial gravel: Sedimentology, v. 20, p. 173–187.

CLIFTON, H. E., 1982, Estuarine Deposits, *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Am. Assoc. Petroleum Geol., Mem. 31, p. 179–190.

COCKBAIN, A. E., 1985, Carboniferous of Western Australia–a review: West. Australia. Geol. Survey, Rept 14, p. 14–35.

COLEMAN, J. M., and WRIGHT, L. D., 1978, Sedimentation in an arid macrotidal alluvial river system; Ord River, Western Australia: Jour. Geology, v. 86, p. 621–642.

COLEMAN, J. M., and PRIOR, D. B., 1982, Deltaic environments, *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Am. Assoc. Assoc. Petroleum Geol., Mem.31, p. 139–178.

COLLINSON, J. D. and THOMPSON, D. B., 1982, Sedimentary structures: George Allen and Unwin, London.

CREEVEY, K., 1966, Kulshill 2 well completion report: Australian Aquitaine Pty Ltd, (unpublished).

DAVID, T. W. E., 1932, Explanatory notes to accompany a new geological map of the Commonwealth of Australia: Australia Council for Scientific and Industrial Research, Sydney.

DOE, T. W., and DOTT, R. G., Jr, 1980, Genetic significance of deformed cross-bedding – with examples from the Navajo and Weber Sandstones of Utah: Jour. Sed. Petrology, v. 50, pt. 3, p. 793–812.

DOW, D. B., 1980, Palaeozoic Rocks of the Hardman, Rosewood and Argyle Basins, East Kimberley Region, Western Australia: Australia BMR, Rec. 1980/54 (unpublished).

DOW, D. B., and GEMUTS, I., 1967, Dixon Range, Western Australia: Australia BMR, 1:250 000 Geological Series Explanatory Notes.

DOW, D. B., and GEMUTS, I., 1969, Geology of the Kimberley Region, Western Australia: the East Kimberley: Australia BMR, Bull. 106.

DOW, D. B., GEMUTS, I., PLUMB, K.A., and DUNNET, D., 1964, The Geology of the Ord River region, Western Australia: Australia BMR, Rec. 1964/104 (unpublished).

DRUCE, E. C., 1969, Devonian and Carboniferous conodonts from the Bonaparte Gulf Basin, Northwestern Australia, and their use in international correlation: Australia BMR, Bull, 98.

DUCHEMIN, A. E., and CREEVEY, 1966, Kulshill No.1, well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

ELLIOTT, T., 1978, Clastic Shorelines: *in* Sedimentary Environments and Facies, *edited by* H. G. READING: Blackwell Scientific Publications, Oxford.

ELLYARD, T., 1980, Drilling and evaluation of the diamond potential within TR 7481H, *in* Report on Stage II of the exploration of TR 7481H on the western side of the entry to the Cambridge Gulf, W.A.: company report *by* P. CAIRNES and ASSOCIATES: West Australia Geol. Survey open file, Item No. 1564, A 11604 (unpublished).

ENOS, P., 1983, Shelf, *in* Carbonate Depositional Environments, *edited by* P. A. SCHOLLE, D. G. BEDOUT, and C. H. MOORE: Am. Assoc. Petroleum Geol., Mem. 33, p. 267–295.

FOORD, A. H., 1890, Description of fossils from the Kimberley District, Western Australia: Geol. Mag., v. 17, p. 78–100.

FRYBERGER, S. G., AHLBRANDT, T. S., and ANDREWS, S., 1979, Origin, sedimentary features, and significance of low angle eolian 'sand sheet' deposits, Great Sand Dunes National Management and Vicinity, Colorado: Jour. Sed. Petrology, v. 49, pt. 3, p. 733–746.

FRYE, L. C. and WILLIAM, H. B., 1962, Morphostratigraphic units in Pleistocene stratigraphy – Note 27, stratigraphic commission: Amer. Assoc. Petroleum Geol. Bull., v. 46, p. 112–113.

GARSIDE, I. E., 1982, Ningbing 1 – well completion report: Australian Aquitaine Petroleum Pty Ltd Report No. PG/174/82 (unpublished).

GARSIDE, I. E., 1983, Weaber 1 – well completion report: Australian Aquitaine Petroleum Pty Ltd Report No. PG/196/83 (unpublished).

GEMUTS, I., and SMITH, J. W., 1968, Gordon Downs, Western Australia: West. Australia Geol. Survey, 1:250 000 Geological Series Explanatory Notes.

GLOVER, J. J. E., RICHARDSON, L. A., and McGILVRAY, E., 1955, Geological and geophysical report on the Keep River area, Bonaparte Gulf Basin: Associated Australian Oilfields, Minad. Report No. NT/BG. 20. (unpublished).

GRANT, N. K., 1971, South Atlantic Benue Trough and Gulf of Guinea Cretaceous triple junction: Geol. Soc. Am. Bull., v. 82, p. 2295–2298.

GREY, K., 1985 Stromatolites from the ?Cambrian Antrim Plateau Volcanics, Lissadell and Gordon Downs 1:250 000 Sheet areas, W.A.: West. Australia Geol. Survey, Palaeontology Report No. 15/1985 (unpublished).

GUILLAUME, R. E. F., 1966, Petroleum geology in the Bonaparte Gulf Basin, N.T.: Commonwealth Min. Metall. Congress, 8th, Proceedings, v. 5, p. 183–196.

HARDMAN, E. T., 1885, Report on the geology of the Kimberley District, Western Australia: West. Australia Parliamentary paper No. 34, Government Printer, Perth.

HARE, R. and ASSOCIATES, and THOMAS, G. A., 1961, Spirit Hill No. 1 well completion report: Oil Development N.L. and Westralian Oil N.L., (unpublished).

HARMS, J. C., SOUTHARD, J. B., and WALKER, R. G., 1982, Structures and sequences in clastic rocks: Lecture Notes for Short Course No.9, Soc. Econ. Paleontol. Mineral.

HAYS, J., 1967, Surfaces and laterites in the Northern Territory, *in* Landform studies from Australia and New Guinea, *edited by* J. N. JENNINGS and J. A. MABBUTT: Australia National University Press, Canberra, p. 182–210.

HEWARD, A. P., 1978, Alluvial fan sequence and megasequence models, with examples from Westphalian D — Stephanian B coalfields, northern Spain, *in* Fluvial Sedimentology, *edited by* A. D. MIALL: Canadian Soc. Petrol. Geol., Mem. 5, p. 669–702.

HILL, D., 1954, Coral faunas of New South Wales and the Devonian of Western Australia: Australia BMR, Bull. 23.

HOWELL, D. G., and NORMARK, W. R., 1982, Sedimentology of submarine fans, *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Am. Assoc. Petroleum Geol., Mem. 31, p. 365–404.

HUDSON, J. D., and COLEMAN, M. L., 1978, Submarine cementation of the Scheck Limestone conglomerate (Jurassic, Austria): isotopic evidence: Neues Jahrbuch Geologie und Palaeontologie, Monatshefte 9, p. 534–544.

HUGHES, R. J., 1978, The geology and mineral occurrences of Bathurst Island, Melville Island, and Cobourg Peninsula, Northern Territory: Australia BMR, Bull. 177.

HUNTER, R. E., 1977, Basic types of stratification in small aeolian dunes: Sedimentology, v. 24, p. 361–387.

INDEN, R. F., and MOORE, C. H., 1983, Beach environment: *in* Carbonate Depositional Environments, *edited by* P. A. SCHOLLE, D. G. BEDOUT and C. H. MOORE: Am. Assoc. Petroleum Geol., Mem. 33, p. 211–266.

JACK, R. L., 1906, The prospects of obtaining artesian water in the Kimberley District: West. Australia Geol. Survey, Bull. 25.

JAQUES, A. L., LEWIS, J. D., and SMITH, C. B., 1986, The Kimberlites and Lamproites of Western Australia: West. Australia Geol. Survey, Bull. 132.

JAMES, N. P., 1979, Shallowing-upward sequences in carbonates: *in* Facies Models, *edited by* R. G. WALKER: Geoscience Canada, Reprint Series 1.

JELL, P. A., 1983, The Early to Middle Cambrian boundary in Australia: *in* Abstracts No. 9: Geol. Soc. Australia., 6th Convention, Canberra, 1983, p. 236.

JONES, P. J., 1968, Upper Devonian Ostracoda and Eridostraca from the Bonaparte Gulf Basin, Northwestern Australia: Australia BMR, Bull. 99.

JONES, P. J., 1971, Lower Ordovician conodonts from the Bonaparte Gulf Basin and the Daly River Basin, Northwestern Australia: Australia BMR, Bull. 117.

JONES, P. J., 1976, Ord Basin, *in* Economic geology of Australia and Papua New Guinea – 3, Petroleum, *edited by* R. B. LESLIE, H. J. EVANS and C. L. KNIGHT: Aust. Inst. Min. Metall. Monograph Series, No. 7, p. 242–246.

JONES, P. J., 1985, Treposellidae (Beyrichiacea: Ostracoda) from the latest Devonian (Strunian): BMR Journal of Australian Geology and Geophysics, v. 9, p. 149–162.

JONES, P. J., and DRUCE, E. C., 1966, Intercontinental conodont correlation of the Palaeozoic sediments of the Bonaparte Gulf Basin, northwestern Australia: Nature, v. 211, p. 357–359.

JUTSON, J. T., 1914, An outline of the physiographical geology (physiography) of Western Australia: West. Australia Geol. Survey, Bull. 61.

JUTSON, J. T., 1934, The physiography (geomorphology) of Western Australia (2nd edition revised): West. Australia Geol. Survey, Bull. 95.

KAULBACK, J. A. and VEEVERS, J. J., 1969, Lower Palaeozoic geology of the Bonaparte Gulf Basin: Australia BMR, Rept 109.

KEMP, E. M., BALME, B. E., HELBY, R. J., KYLE, R. A., PLAYFORD, G., and PRICE, P. L., 1977, Carboniferous and Permian palynostratigraphy in Australia and Antarctica: a review: BMR Journal of Australian Geology and Geophysics, v. 2, p. 177–208.

KLEIN, G., de V., 1977, Clastic Tidal Facies: Continuing Education Publication Company, Champaign, Illinois.

KOCUREK, G., 1981, Significance of interdune deposits and bounding surfaces in aeolian dune sands: Sedimentology, v. 28, p. 753–780.

KOCUREK, G., and DOTT, R. H., Jr. 1981, Distinction and uses of stratification types in the interpretation of eolian sand: Jour. Sed. Petrology, v. 51, p. 579–595.

LAWS, R. A., 1981, The petroleum geology of the onshore Bonaparte Basin: APEA Jour., v. 21, pt. 1, p. 5–15.

LAWS, R. A., and BROWN, R. S., 1976, Petroleum Geology of the southeastern Bonaparte Gulf Basin, *in* Economic geology of Australia and Papua New Guinea — 3, Petroleum, *edited by* R. B. LESLIE, H. J. EVANS and C. L. KNIGHT: Aust. Inst. Min. Metall., Monograph Series, No. 7, p. 200–208.

Le BLANC, M. C., 1964, Bonaparte No. 1 well completion report: Alliance Oil Development Australia N.L., (unpublished).

Le BLANC, M. C., 1965. Bonaparte No. 2 well completion report: Alliance Oil Development Australia N.L., (unpublished).

LEE. R. J., 1982, Aquitaine Australia Minerals Pty Ltd Aquitaine–Mimets–St. Joe MG 1161 vol. 2, Summary of 1979–1981 Biostratigraphic studies WA–NT: Aquitaine Australia Minerals Pty Ltd report (unpublished).

LESLIE, R. B., EVANS, H. J. and KNIGHT, C. L. (*editors*), 1976, Economic geology of Australia and Papua New Guinea — 3, Petroleum: Aust. Inst. Min. Metall., Monograph Series, No. 7.

LLOYD, A. R., 1968, Possible Miocene marine transgression in northern Australia: Australia BMR, Bull. 80.

MacDONALD, G. A., 1972, Volcanoes: Englewood Cliffs, Prentice-Hall Inc.

MAHONY, D. J., 1922, Report on oil prospects near Ord-Negri River junction, East Kimberley District: "West Australian" Newspaper, June 15th, 1922.

MAITLAND, A. G., and MONTGOMERY, A., 1924, The geology and mineral industry of Western Australia: West. Australia Geol. Survey, Bull. 89

MAMET, B. L., and BELFORD, D. J., 1968, Carboniferous foraminifera, Bonaparte Gulf Basin, northwestern Australia: Micropaleontology, v. 14, No. 3, p. 339–347.

MAMET, B. A. and ROUX, A., 1983, Algues Devono-Carboniferes de L'Australie: Revue de Micropaleontologie, v. 26, pt. 2, p. 63–131.

MARSTON, R. J., 1979, Copper mineralization in Western Australia: West. Australia Geol. Survey, Mineral Resources Bull. 13.

MATHESON, R. S., and TEICHERT, C., 1948, Geological reconnaissance in the eastern portion of the Kimberley District, Western Australia: West. Australia Geol. Survey, Ann. Rept 1945, p. 73–87.

McBAIN, D. R., 1982, Moogarooga TR 7886H and Oakes Creek TR 7885H, Western Australia, Final Report CRAE report: West Australia Geol. Survey, Open File No. S 1940 A2 (unpublished).

McCUBBIN, D. G., 1982, Barrier-island and strand plain facies, *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Am. Assoc. Petroleum Geol., Mem. 31, p. 247–280.

McKEE, E. D., (*editor,*) 1979, A study of global sand seas: U.S. Geol. Survey, Prof. Paper 1052.

McWHAE, J. R. H., PLAYFORD, P. E., LINDER, A. W., GLENISTER, B. F., and BALME, B. E., 1958, The stratigraphy of Western Australia: Geol. Soc. Australia Jour., v. 4, pt. 2.

MEAKINS, A., 1983, Geology and genesis of the Argyle alluvial diamond deposits, Kimberley region, Western Australia, *in* Geochemical exploration in arid and deeply weathered environments. Geochemistry and genesis of ore deposits associated with weathering, *edited by* R. DAVY, C. R. M. BUTT, and T. A. BALLINGER: Assoc. Expl. Geochemists, Regional Meeting, Perth 1983, Abstracts, p. 54–56.

MIALL, A. D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary, *in* Fluvial Sedimentology, *edited by* A. D. MIALL: Canadian Soc. Petrol. Geol., Mem. 5, p. 597–604.

MIALL, A. D., 1982, Analysis of fluvial depositional systems: Am. Assoc. Petroleum Geol., Education Course Note Series, 20.

MIDDLETON, G. V., and HAMPTON, M. A., 1973, Sediment gravity flows: mechanics of flow and deposition, *in* Turbidites and deep-water sedimentation: Soc. Econ. Paleont. Mineral., Short Course Notes, p. 1–38.

MORY, A. J., and BEERE, G. M., 1985, Palaeozoic stratigraphy of the Ord Basin, Western Australia and Northern Territory: West. Australia Geol. Survey, Rept. 14, p. 36–45.

MORY, A. J., and CRANE, D. T., 1982, Early Carboniferous *Siphonodella* (Conodonta) faunas from eastern Australia: Alcheringa, v. 6, p. 275–303.

NOAKES, L. C., ÖPIK, A. A., and CRESPIN, I., 1952, Bonaparte Gulf Basin, Northwestern Australia; a stratigraphical summary with special reference to the Gondwana System: International Geol. Congress, 19th (Gondwana Symposium) Algiers, 1950, p. 91–106.

ÖPIK, A. A., 1950, Notes on Palaeozoic stratigraphy, Cambridge Gulf area: Australia BMR, Rec. 1950/31 (unpublished).

ÖPIK, A. A., 1967, The Ordian stage of the Cambrian and its Australian Metadoxididae: Australia BMR, Bull. 92, p. 133–165.

PLAYFORD, G., 1982, A latest Devonian palynoflora from the Buttons beds, Bonaparte Gulf Basin, Western Australia: BMR Journal of Australian Geology and Geophysics, v. 7, p. 149–157.

PLAYFORD, P. E., 1969, Devonian carbonate complexes of Alberta and Western Australia: a comparative study: West. Australia Geol. Survey, Rept 1.

PLAYFORD, P. E., 1980, Devonian "Great Barrier Reef" of Canning Basin, Western Australia: Am. Assoc. Petroleum Geol. Bull. 64, p. 814–840.

PLAYFORD, P. E., 1982, Devonian reef prospects in the Canning Basin: implications of the Blina oil discovery: APEA Jour., v. 22, p. 258-271.

PLAYFORD, P. E., 1984, Platform-margin and marginal-slope relationships in Devonian reef complexes of the Canning Basin, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Geol. Soc. Australia/PESA Symposium, Perth, 1984, Proceedings p. 189–214.

PLAYFORD, P. E., COPE, R. N., COCKBAIN, A. E., LOW, G. H., and LOWRY, D. C., 1975, Phanerozoic, *in* Geology of Western Australia: West. Australia Geol. Survey, Mem. 2, p. 223—432.

PLAYFORD, P. E., VEEVERS, J. J., and ROBERTS, J., 1966, Upper Devonian and possible Lower Carboniferous reef complexes in the Bonaparte Gulf Basin: Australian Jour. Sci., v. 28, p. 436–7.

PLUMB, K. A., 1968, Lissadell, Western Australia: West. Australia Geol. Survey, 1:250 000 Geological Series Explanatory Notes.

PLUMB, K. A., and GEMUTS, I., 1976, Precambrian geology of the Kimberley Region, Western Australia: International Geological Congress, 25th, Excursion Guide No. 44C, Sydney, 1976.

PONTIFEX, I. R., and SWEET, I. D., 1972, Auvergne, Northern Territory: Australia BMR, 1:250 000 Geological Series Explanatory Notes.

POSTMA, G., 1983, Water escape structures in the context of a depositional model of a mass flow dominated conglomeratic fan-delta (Abrioja Formation, Pliocene, Almeria Basin, S.E Spain): Sedimentology, v. 30, p. 91–103.

RADKE, B. M., and MATHIS, R. L., 1980, On the formation of saddle dolomite: Jour. Sed. Petrology, v. 50, p. 1149–1168.

READING, H. G., (*editor*) 1978, Sedimentary Environments and Facies: Blackwell Scientific Publications, Oxford.

REEVES, F., 1949, Geology and oil possibilities of the Bonaparte Gulf Basin: Vacuum Oil Co. Rept (unpublished).

REEVES, F., 1951, Australian oil possibilities: Am. Assoc. Petroleum Geol. Bull. v. 35, p. 2479–2525.

REINECK, H. E., and SINGH, I. B., 1975, Depositional sedimentary environments with reference to terrigenous clastics: Springer-Verlag, Berlin.

RINGROSE, C. R., in press, Studies of selected carbonate-hosted lead-zinc deposits in the Kimberley region: West. Australia Geol. Survey, Rept.

ROBERTS, H. G., GEMUTS, I., and HALLIGAN, R., 1972, Adelaidean and Cambrian stratigraphy of the Mount Ramsay 1:250 000 Sheet area, Kimberley region, Western Australia: Australia BMR, Rept 150.

ROBERTS, J., 1971, Devonian and Carboniferous brachiopods from the Bonaparte Gulf Basin, Northwestern Australia: Australia BMR, Bull. 122.

ROBERTS, J., JONES, P. J., and DRUCE, E. C., 1967, Palaeontology and correlations of the Upper Devonian of the Bonaparte Gulf Basin, Western Australia and Northern Territory, *in* International symposium on the Devonian System, *edited by* D. H. OSWALD: Alberta Soc. Petroleum Geologists, v. 2, p. 565–578.

ROBERTS, J., and VEEVERS, J. J., 1973, Summary of BMR studies of the onshore Bonaparte Gulf Basin 1963–71: Australia BMR, Bull. 139, p. 29–58.

ROSS, G. M., 1983, Bigbear Erg: a Proterozoic intermontane eolian sand sea in the Hornby Bay Group, Northwest Territories, Canada, *in* Eolian Sediments and Processes, *edited by* M. E. BROOKFIELD and T. S. AHLBRANDT: Developments in Sedimentology 38, Elsevier, Amsterdam, p. 483–519.

ROWLEY, M., and LEE, R. J., 1986, The Sorby Hills, W.A., lead-silver-zinc province, *in* Geology and Exploration, *edited by* D. A. BERKMAN: Congress of the Council of Mining and Metallurgical Institutions, and the Australian Institute of Mining and Metallurgy, 13th, Singapore, 1986, Publications, v.2, p. 173–180.

RUPKE, N. A., 1978, Deep clastic seas, *in* Sedimentary Environments and Facies, *edited by* H. G. READING: Blackwell Scientific Publications, Oxford.

RUST, B. R., 1979, Coarse alluvial deposits, *in* Facies Models, *edited by* R. G. WALKER: Geoscience Canada, Reprint Series 1, p. 1–8.

SHINN, E. A., 1983, Tidal Flat, *in* Carbonate Depositional Environments, *edited by* P. A. SCHOLLE, D. G. BEDOUT, and C. H. MOORE: Am. Assoc. Petroleum Geol., Mem. 33, p. 171–210.

SIMPSON, E. S., 1951, Minerals of Western Australia, v.2: Government Printer, Perth.

STEEL, R. J., and GLOPPEN, T. G., 1980, Late Caledonian (Devonian) basin formation, western Norway – signs of strike-slip tectonics during infilling, *in* Sedimentation in oblique-slip mobile zones, *edited by* H. G. READING and P. F. BALLANCE: International Association of Sedimentologists, Special publication, No. 4, p. 79–103.

STEWART, G. A., 1970, Lands of the Ord–Victoria area, Western Australia and Northern Territory: Aust. CSIRO, Land Res. Ser. 28.

SWEET, I. P., MENDUM, J. R., BULTITUDE, R. J., and MORGAN, C. M., 1974, The geology of the southern Victoria River region, Northern Territory: Australia BMR, Rept 167.

TANNER, W. F., 1971, Numerical estimates of ancient waves, water depth and fetch: Sedimentology, v. 16, p. 71–88.

THOM, B. G., WRIGHT, L. D., and COLEMAN, J. M., 1975, Mangrove ecology and deltaic-estuarine geomorphology Cambridge Gulf–Ord River, Western Australia: Jour. Ecology, v. 63, p. 203–232.

THOMAS, G. A., 1962, The Carboniferous stratigraphy of the Bonaparte Gulf Basin: Compte Rendu du Quatrième Congres pour l'advancement des études de stratigraphie et de geologie du Carbonifère, Heerlen, 1958, Tome III, 1962, p. 727-732.

THOMAS, G. A., 1965, *Delepinea* in the Lower Carboniferous of northwest Australia: J. Paleontology, v. 39, pt. 1, p. 97–102.

THOMPSON, R. W., 1975, Tidal-flat sediments of the Colorado River delta, northwestern Gulf of California, *in* Tidal Deposits, *edited by* R. N. GINSBURG: Springer-Verlag, New York, p. 57–66.

TRAVES, D. M., 1949, Preliminary report on survey of Ord–Victoria Region, Northern Australian Regional Survey: Australia BMR, Rec. 1949/22 (unpublished).

TRAVES, D. M. 1955, The geology of the Ord–Victoria region, Northern Australia: Australia BMR, Bull. 27.

TRUSWELL, E. M., 1981, Palynological examination of samples from Aquitaine Minerals Pty Ltd corehole WBN 5003, Bonaparte Gulf Basin: Australia BMR, Prof. Opinion 1981/004 (unpublished).

UTTING, E. P., 1958, Progress geological report, Permit No. 3, Bonaparte Gulf Basin (1957): Westralian Oil Ltd (unpublished).

VAIL, P. R., MITCHUM, R. M., and THOMPSON, S., 1977, Global cycles of sea level changes, *in* Seismic stratigraphy — applications to hydrocarbon exploration, *edited by* C. E. PAYTON: Am. Assoc. Petrol. Geol., Mem. 26, p. 83–98.

VAN DE KAMP, P. C., HARPER, J. D., CONIFF, J. J., and MORRIS, D. A., 1974, Facies relations in the Eocene–Oligocene in the Scinta Ynez Mountains, California: Geol. Soc. London Jour., v. 130, p. 545–565.

VEEVERS, J. J., 1969, Sedimentology of the Upper Devonian and Carboniferous Platform Sequence of the Bonaparte Gulf Basin: Australia BMR, Bull. 109.

VEEVERS, J. J., 1970, Upper Devonian and Lower Carboniferous calcareous algae and stromatolites from the Bonaparte Gulf Basin, northwestern Australia: Australia BMR, Bull. 116, p. 173–88.

VEEVERS, J. J., JONES, J. G. and POWELL, C.McA., 1982, Tectonic Framework of Australia's sedimentary basins: APEA Jour., v. 22, pt. 1, p. 283–300.

VEEVERS, J. J., and ROBERTS, J., 1966, Littoral talus breccia and probable beach rock from the Visean of the Bonaparte Gulf Basin: Geol. Soc. Australia Jour., v. 13, p. 387–403.

VEEVERS, J. J., and ROBERTS, J., 1968, Upper Palaeozoic rocks, Bonaparte Gulf Basin of Northwestern Australia: Australia BMR, Bull. 97.

WADE, A., 1924, Petroleum prospects, Kimberley district of Western Australia and Northern Territory: Report to Commonwealth Parliament, Australia, No. 142.

WALKER, K. R., SHANMUGAM, G., and RUPPEL, S. C., 1983, A model for carbonate to terriginuous clastic sequences: Geol. Soc. Am. Bull., v. 94, p. 700–712.

WALKER, R. G., 1978, Deep water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps: Am. Assoc. Petroleum Geol. Bull., v. 62, pt. 6, p. 932–966.

WALKER, R. G., and CANT, D. J., 1979, Sandy fluvial systems, *in* Facies Models, *edited by* R. G. WALKER: Geoscience Canada, Reprint Series 1, p. 23–32.

WALTER, M. R., 1972, Stromatolites and the biostratigraphy of the Australian Precambrian and Cambrian: Palaeont. Assoc., Spec. Papers in Palaeontology, 11.

WEIMAR, R. J., HOWARD, J. D., and LINDSAY, D. R., 1982, Tidal Flats, *in* Sandstone Depositional Environments, *edited by* P. A. SCHOLLE and D. SPEARING: Assoc. Petroleum Geol., Mem. 31, p. 191–246.

WHITEHEAD, B. R., and FAHEY, G. M., 1985, Geology of Keep River National Park: Northern Territory Geological Survey, Rept 1.

WILLIAMS, P. R., 1982, Final report of exploration TR's 8689H—8694H, Cambridge Gulf Western Australia: Utah Development Co. report (unpublished): West. Australia Geol. Survey, Open File No. S 2104 A1.

WILSON, J. L., 1975, Carbonate facies in geologic history: Springer-Verlag, New York.

WILSON, J. L., and JORDAN, C., 1983, Middle Shelf, *in* Carbonate Depositional Environments, *edited by* P. A. SCHOLLE, D. G. BEDOUT and C. H. MOORE: Am. Assoc. Petroleum Geol., Mem. 33, p. 297–344.

WRAY, J. L., 1977, Calcareous algae: Developments in palaeontology and stratigraphy, 4: Elsevier, Amsterdam.

YEATES, A. N., CROWE, R. W. A., TOWNER, R. R., WYBORN, L. A. I., and PASSMORE, V. L., 1975, Notes on the geology of the Gregory Sub-basin and adjacent areas of the Canning Basin, Western Australia: Australia BMR, Rec. 1975/77 (unpublished).

YOUNG, R. W., 1986a, Tower Karst in Sandstone: Bungle Bungle massif, northwestern Australia: Zeitschrift für Geomorphologie, Neue Folge, v. 30, pt. 2, p. 189–202.

YOUNG, R. W., 1986b, Sandstone Landforms in the Tropical East Kimberley Region, Northwestern Australia: Journal of Geology, v. 95, p. 205-218.

ZHANG, W. T. and LIN, H. L., 1980, Redlichiida, *in* Cambrian trilobite faunas of southwestern China, *by* W. T. ZHANG, W. H. LU, Z. L. ZHU, Y. Y. QUAIN, H. L. LIN, Z. Y. ZHON, S. G. ZHANG, and J. Z. YUAN: Palaeontologia Sinica, vol. 159, (new ser. B) No. 16, p. 61–229.

APPENDIX

GAZETTEER OF LOCALITIES MENTIONED IN TEXT

Locality		*Latitude (S)* D	M	S	*Longitude (E)* D	M	S
Abney Hill		15	44	00	128	45	10
Adele Island 1 (Browse Basin)		15	30	45	123	09	25
Agate Hills		17	50	20	128	36	00
Alice Hill		15	01	40	128	29	00
Argyle homestead (submerged)		16	17	30	128	47	20
Argyle Pipe, AK1		16	42	50	128	23	20
Ashburton Range (NT)		18	06		133	43	
Attack Spring (Wungabal)		14	54	00	128	41	50
Behn River		16	42	00	129	10	00
	to	16	23	20	128	50	10
Billy Goat Creek		16	30	30	128	26	20
	to	16	30	20	128	32	40
Bingy Bingy Springs (NT)		17	35	40	129	09	20
Birrindudu homestead (NT)		18	24	00	129	26	00
Blackfella Rockhole (NT)		17	23	30	129	06	30
Blatchford Escarpment		16	14	40	128	22	20
	to	16	29	50	128	21	10
Boll Creek		17	17	30	128	31	30
Bolgumirri (House Roof Hill)		15	32	50	128	30	20
Bonaparte 1		15	01	00	128	44	40
Bonaparte 2		15	05	07	128	43	16
Bow River		17	14		128	01	
	to	17	37		128	39	
Brolga Spring		14	53	50	128	34	00
Brook Creek		17	39	30	128	49	50
	to	17	32	50	128	42	40
Buchanan Creek		17	22	30	128	30	20
	to	17	50	30	128	36	20
Buffalo Tank		15	17	20	128	21	00
Bulka Hills (Canning Basin)		19	04		126	28	
Bungle Bungle outstation		17	20	30	128	20	40
Bungle Bungle Range		17	25		128	25	
Burt Range		15	48		128	58	
Burt Range Amphitheatre (NT)		15	48		129	01	
Burvill Point		15	14	50	128	41	30
Buttons Crossing		15	37	00	128	41	20
Buttons Gap		15	36	30	128	40	10
Calf Spring		15	02	00	128	52	10
Cambridge Gulf		15	00		128	10	
Cambridge 1		14	17	28	128	25	57
Camel Back Hills		16	45	40	128	53	40
Carlton Hill homestead		15	29	20	128	32	00
Carr Boyd Ranges		16	10		128	31	
Charra Rockhole		17	53	00	128	44	40
Christmas Creek (Canning Basin)		19	05		127	33	
	to	18	30		125	23	
Clark Jump Up		15	26	40	128	38	00
Cleanskin Bore		15	05	10	128	56	00
Cockatoo Spring (Maudoobar)		15	56	50	128	57	30
Conglomerate Hill		16	24	10	128	21	00
Daly River (NT)		14	39		131	42	
	to	13	19		130	15	
Dicks Yard		16	36	10	128	44	50
Dillon Spring		15	57	00	128	24	40
Dixon Range		17	40		128	20	

Locality		*Latitude (S)* D	M	S	*Longitude (E)* D	M	S
Djigumirri (False House Roof Hill)		15	33	00	128	34	10
Djilirri		15	15	00	128	40	20
Doon Doon homestead		16	18	40	128	14	40
Doughboy Hill		17	31	50	128	38	30
Dunham River		16	25	50	127	58	50
	to	15	46	30	128	41	10
Eclipse Yard		15	19	40	128	21	30
Eight Mile Creek		15	53	50	128	57	00
	to	15	37	20	128	53	50
Elephant Hill		15	03	00	128	12	00
Elvire River		18	13	20	128	45	20
	to	17	51	00	128	12	00
Enga Ridge		15	48	50	128	56	20
False House Roof Hill (Djigumirri)		15	33	00	128	34	10
Flapper Hill (NT)		15	11		129	24	
Flying Fox Creek		16	37	20	128	20	40
	to	16	33	10	128	29	40
Fox River homestead		18	25	40	128	02	00
Galawa (Old Dip Yard)		15	27	50	128	27	00
Galloping Creek		16	37	40	128	22	40
	to	16	34	10	128	29	00
Gap Point		15	44	30	128	17	20
Garimala (Surprise Creek)		15	12	30	128	41	50
	to	15	10	40	128	37	30
Glass Hill		17	16	40	128	41	10
Glenhill homestead		16	32	40	128	21	20
Goose Hole		17	39	10	128	30	30
Gordon Downs homestead		18	45	00	128	35	00
Great Antrim Plateau		18	05		128	20	
Gum Creek		15	21	00	128	50	40
Halls Creek		18	13	30	127	40	00
Hardman Range		17	52	10	128	20	40
Hargreaves Hills		15	19		128	33	
Hart Spring		15	19	10	128	26	40
Headleys Knob (NT)		17	28	50	129	00	50
Horse Creek Well		17	01	40	128	34	50
House Roof Hill (Bolgumirri)		15	32	50	128	30	20
Hudson Creek		17	15	30	128	57	50
	to	17	15	10	128	57	30
Jeremiah Hills		15	26		128	44	
Joseph Bonaparte Gulf		14	50		128	50	
Kamilili (Long Spring)		14	53	40	128	39	00
Keep River (NT)		16	13		129	15	
	to	15	10		129	11	
Keep River National Park (NT)		15	44	00	129	00	00
	to	15	44	00	129	06	00
	to	15	59	00	129	04	00
	to	15	59	00	129	00	00
Keep River 1 (NT)		15	10	05	129	05	22
Kellys Knob		15	46	00	128	44	30
Knob Peak		15	50	40	128	34	20
Koolpinyah homestead		12	23	00	131	10	00
Kulshill 1 (NT)		14	21	47	129	32	33
Kununurra		15	46	30	128	43	40
Lake Argyle		16	18		128	48	
Langfield Point		15	49	10	128	59	40
Legune homestead (NT)		15	13	10	129	26	50
Lesueur 1		13	57	09	128	07	33
Leveque 1 (Browse Basin)		15	45	12	122	00	18
Limestone Creek		16	43	20	128	23	00
	to	16	38	30	128	33	40

Locality		*Latitude (S)* D	M	S	*Longitude (E)* D	M	S
Limestone Mill		15	23	10	128	44	00
Linnekar Creek		17	52	50	128	40	20
	to	17	30	00	128	43	50
Londonderry 1 (Browse Basin)		13	36	53	124	30	43
Long Spring (Kamilili)		14	53	40	128	39	00
Malley Spring		17	02	10	128	28	50
Marella Hole		18	07	40	128	41	30
Martin Bluff		15	37	00	128	51	00
Margaret River homestead		18	37	00	127	51	40
Matheson Ridge		15	52		128	53	
Maudoobar (Cockatoo Spring)		15	56	50	128	57	30
Maxwell Plains		15	51		128	47	
Mermaid Point		15	06	10	128	12	00
Milligans Hills		15	48		129	00	
Milligans 1 (NT)		15	39	00	129	00	30
Milligans 2 (NT)		15	36	50	129	00	55
Mongrel Downs homestead (NT)		20	34	10	129	43	30
Moogarrooga Creek		15	06	30	128	50	10
	to	15	03	00	129	04	10
Moonlight Valley		17	03		128	34	
Mount Brooking		16	05	00	128	55	40
Mount Buchanan (Purralili)		17	19	20	128	37	10
Mount Cecil		15	44	20	128	48	40
Mount Close		16	57	20	128	50	30
Mount Connection		15	14	20	128	16	00
Mount Cyril		15	46	20	128	44	50
Mount Elder (J40)		17	12	50	128	55	00
Mount Hensman		16	00	20	128	57	20
Mount Mahony		15	32	30	128	36	20
Mount Panton (NT)		17	16	15	129	12	40
Mount Rob		15	51	20	128	14	50
Mount Septimus		15	43	30	128	59	00
Mount Wittenoom		18	34	30	128	51	20
Mount Zimmerman		15	46	20	128	59	10
Mulali (Reedy Creek)		15	31	20	128	29	50
	to	15	29	50	128	22	20
Negri River		17	35	10	129	19	30
	to	15	46	20	128	59	10
Nelson Springs (NT)		17	20	10	129	17	00
Nicholson homestead		18	02	00	128	54	00
Nicholson River		18	00	40	129	00	00
	to	17	34	10	128	38	40
Ningbing homestead		15	14	40	128	40	40
Ningbing Range		15	06		128	37	
Ningbing 1		15	10	54	128	40	52
Oakes Creek		15	18	50	128	52	40
	to	15	19	40	129	05	20
Oakes Mountain		19	04	20	128	21	30
Okes-Durack 1		17	17	40	128	58	30
Old Dip Yard (Galawa)		15	27	50	128	27	00
Onslow Hills		14	59		128	07	
Opik Hill		15	04	20	128	37	50
Osmond Creek		17	14	00	128	18	10
	to	17	09	40	128	50	40
Osmond Range		17	10		128	30	
Ord River		17	19	20	128	18	30
	to	15	12	10	128	12	00
Ord River Dam		16	07	20	128	44	20
Ord River homestead		17	23	10	128	55	20
Ord River Irrigation Area		15	39		128	43	
Overland Spring (NT)		17	13	20	129	04	40
Paddys Bore (Utting Gap)		14	58	10	128	35	50
Pander Ridge		15	28	20	128	41	00
Parkers yard		17	12	20	128	52	00

Locality		*Latitude (S)* D	M	S	*Longitude (E)* D	M	S
Pelican Island 1		14	46	19	128	46	27
Piccaninny Creek		17	25	20	128	22	10
	to	17	40	40	128	28	50
Pincombe Range		15	34		128	52	
Point Spring		15	24	30	128	53	10
Pretlove Hills		15	24		128	35	
Ragged Range		16	24		128	22	
Reedy Creek (Mulali)		15	21	30	128	29	50
	to	15	29	50	128	22	20
Revolver Creek		16	20	00	128	27	00
	to	16	15	00	128	35	00
Rob Roy 1 (Browse Basin)		13	58	16	124	11	57
Rosewood homestead (NT)		16	27	40	128	00	30
Siggins Spring		15	17	20	128	37	10
Skewthorpe Ridge		15	27	20	128	36	50
Skull Creek		15	16	00	128	53	20
	to	15	08	30	129	02	40
Skull 1		15	17	07	128	57	17
Smoke Creek		16	41	30	128	23	10
	to	16	33	10	128	29	40
Sorby Hills		15	28		128	58	
Spirit Hill (NT)		15	34		129	04	
Spirit Hill 1 (NT)		15	30	20	129	14	18
Spring Creek homestead		16	49	10	128	51	50
Steeple Peak		15	36	30	128	49	10
Sturt Creek homestead		19	10	00	128	10	00
Surprise Creek (Garimala)		15	12	30	128	41	50
	to	15	10	40	128	37	30
Tanmurra Bore		15	05	40	128	37	50
Tanmurra Creek		15	05	20	128	40	00
	to	15	04	10	128	33	40
Tarrara Bar		15	33	50	128	41	00
Tennant Creek (NT)		19	39	00	134	11	00
Texas Downs homestead		17	00	30	128	28	00
The Gorge		15	10	50	128	37	40
The Needles		14	47	50	128	25	00
Top Springs homestead (NT)		16	32	40	131	48	20
Trig station J32 (Hardman, 1885)		18	02	40	128	16	50
Trigg station J37 (Hardman, 1885)		17	31	30	128	37	00
Trig station J40 (Hardman, 1885)		17	12	50	128	55	00
Turkey Creek		17	02	00	128	12	50
Turner outstation		17	50	00	128	17	30
Utting Gap (Paddys Bore)		14	58	10	128	35	50
Victoria River (NT)		17	52		130	05	
	to	15	00		129	35	
Waggon Creek		15	23	40	128	35	20
	to	15	20	50	128	36	00
Wave Hill homestead (NT)		17	29	00	130	57	00
Weaber Plain		15	25		128	55	
Weaber Range		15	20		128	50	
Weaber 1 (NT)		15	21	10	129	07	49
Westwood Creek		14	49	10	128	28	10
	to	14	51	10	128	28	00
White Mountain		17	15	40	128	58	00
Wild Dog Bore		16	13	40	128	21	30
Wungabal (Attack Spring)		14	54	00	128	41	50
Wyndham		15	29	20	128	07	10

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BONAPARTE AND ORD BASINS: NORTHERN SHEET

REFERENCE

CAINOZOIC — QUATERNARY

Qa Alluvium — sand, silt and clay
Qc Tidal flats and mangrove swamps — silty clay, black organic clay, minor gypsum and salt
Qe Beach ridges — yellow sand, medium grained

TERTIARY

Czs Sand plain
Czb Black soil
Czl Lateritic soil
Czk Caliche

Tp Laterite

BONAPARTE BASIN

Carlton Shelf | Basin | Burt Range Shelf

PERMIAN — LATE CARBONIFEROUS

Pk **KEEP INLET FORMATION :** medium to fine sandstone and pebbly sandstone, laminated, massive and cross-bedded; minor massive pebble-boulder conglomerate; minor shale with dropstones; fan-delta and glaciomarine

LATE CARBONIFEROUS

Cw **Weaber Group :** undifferentiated
Cup **POINT SPRING SANDSTONE :** grey, medium to fine sandstone and pebbly sandstone, parallel-bedded, laminated, medium cross-bedded; bioturbated and fossiliferous, minor shale; deltaic
Cuk **Border Creek Member :** medium to fine pebbly sandstone and sandstone, minor pebble-cobble conglomerate; medium to thick planar and trough cross-bedded; minor laminated shale and siltstone; fluvio-deltaic
Cut **TANMURRA FORMATION :** sandstone, limestone, dolomite; ? deltaic (subsurface only — section A–A')
Clr **BURVILL FORMATION :** very fine to fine sandstone, thin parallel and low angle cross-bedded; minor medium to coarse sandy limestone, medium to thick beds; fossiliferous, bioturbated; offshore, prodelta
Clu **UTTING CALCARENITE :** grey and yellow-brown sandy limestone (packstone, grainstone), and shale; offshore
Clw **WAGGON CREEK FORMATION :** fine to coarse sandstone and minor conglomerate, massive, graded, thin to medium parallel-bedded; shale and dolomite boulders locally common; minor laminated shales; fossiliferous, submarine fan
Clm **MILLIGANS FORMATION :** black and dark-grey shale, partly calcareous; minor limestone; rare fine to medium sandstone, thin to thick beds; diverse fauna; offshore

EARLY CARBONIFEROUS — VISEAN

Langfield Group
Clz **ZIMMERMAN SANDSTONE :** medium to fine quartz arenite and quartz wacke, parallel and medium to thin cross-bedded; minor laminated siltstone and shale; bioturbated and fossiliferous; lower shoreface, offshore
Cls **SEPTIMUS LIMESTONE :** sandy limestone (packstone, grainstone), parallel, massive and thick planar cross-bedded; minor medium to coarse calcareous sandstone, thin to medium trough cross-bedded; diverse fauna; shoreface, foreshore, shelf
Cle **ENGA SANDSTONE :** very fine to medium quartz arenite, minor calcareous sandstone, parallel-bedded, massive, common *Skolithos*, minor cross-bedding; minor massive and laminated siltstone and shale; barrier
Clb **BURT RANGE FORMATION :** Lower : limestone, minor sandy limestone, rare calcareous sandstone. Upper : very fine to fine calcareous sandstone and sandstone, parallel-bedded and massive, massive limestone; diverse fauna; locally dolomitized; shelf, shoreface

EARLY CARBONIFEROUS — TOURNAISIAN

D-Co **BONAPARTE FORMATION :** dark shale, siltstone and sandstone; offshore (subsurface only — section A–A')

FAMENNIAN

Dun **Ningbing Group :** undifferentiated reef complex
Dug **GARIMALA LIMESTONE :** limestone breccia; marginal slope
Dub **BUTTONS FORMATION :** well-bedded limestone with sandstone; back-reef
Dul **WUNGABAL LIMESTONE :** red "scheck" breccia; marginal slope
Dui **KAMILILI FORMATION :** flaggy limestone and shale; marginal slope to basin
Dud **DJILIRRI LIMESTONE :** well-bedded limestone; back-reef (b), massive microbial limestone; reef-margin (r), limestone breccia; marginal slope (f)
Duc **Cockatoo Group :** undifferentiated, generally along faults; silicified, strongly jointed sandstones
Duh **HARGREAVES FORMATION :** very fine to medium quartz arenite, glauconitic, massive, laminated, parallel and medium cross-bedded; minor dolomite and dolomitic sandstones, massive to laminated; minor siltstones; fossiliferous, bioturbated; shallow marine, barrier complex
Duw **Wentwood Member :** massive stromatoporoid — *Renalcis* — stromatolite limestone, bedded fossiliferous limestone and sandstone; reef margin to back reef
Dus **Siggins Spring Member :** fine to medium quartz arenite, thin to medium cross-bedded, minor medium parallel-bedded; minor siltstone; fluvial
Dum **MAUDODBAR SANDSTONE :** fine to medium quartz arenite, well sorted, medium to thick planar cross-beds, minor parallel and medium trough cross-bedding; barite rosettes; eolian
Due **CECIL SANDSTONE :** fine to medium quartz arenite; pebbly sandstone and minor pebble-cobble conglomerate, medium to thin parallel and cross-bedded; minor siltstone; wood fragments; fluvial
Duf **GALLOPING CREEK FORMATION :** fine to very coarse arkose and pebbly arkose, cross-bedded and laminated; red pebble-boulder conglomerate, massive and cross-bedded; alluvial fan, fluvial
Dua **ABNEY SANDSTONE :** red, quartz arenite and arkose, medium to thin parallel and cross-bedded, laminated, scattered granules, locally pebbly; locally bioturbated, sparsely fossiliferous; tidal, fluvial
Duu **KUNUNURRA FORMATION :** very fine to fine quartz arenite, thin to medium parallel-bedded, laminated; minor dolomitic sandstone and shale, massive to laminated; fossiliferous, *Cruziana* ; shallow marine
Duk **KELLYS KNOB SANDSTONE :** fine to medium quartz arenite, well sorted, medium to thick planar cross-bedded, minor parallel and medium trough cross-bedded; local bioturbation; eolian, fluvial, tidal
Dur **RAGGED RANGE CONGLOMERATE :** red, massive pebble-boulder conglomerate; medium to thick cross-bedded pebbly sandstone; minor fine to very fine sandstone, laminated to thin parallel-bedded; alluvial fan
Dup **STEEPLE PEAK SANDSTONE :** red, quartz arenite and arkose, medium to thin parallel and cross-bedded, laminated, scattered granules, locally pebbly; rare thick pebble-boulder conglomerate; locally bioturbated, sparsely fossiliferous; tidal, fluvial
Duy **CYRIL SANDSTONE :** fine to medium quartz arenite, pebbly sandstone, and minor pebble-boulder conglomerate, medium to thin parallel and cross-bedded; minor siltstone, rare local bioturbation; fluvial

LATE DEVONIAN — FRASNIAN

ORD BASIN

Db **BOLL CONGLOMERATE :** red, pebble-boulder conglomerate, massive; pebbly sandstone and quartz arenite, medium to thick cross-bedded, minor parallel-bedded; minor siltstone; alluvial fan
Dd **Mahony Group :** (southern sheet only)
GLASS HILL SANDSTONE : medium to fine quartz arenite and minor pebbly sandstone, medium cross and parallel-bedded; minor siltstone; rare conglomerate; fluvial
Dc **PURRALILI SANDSTONE :** medium quartz arenite, well sorted, medium to thick planar cross-bedded, low angle cross-bedded, minor massive and parallel-bedded; eolian, fluvial

ORDOVICIAN

BONAPARTE BASIN

Olp **PANDER GREENSAND :** fossiliferous, glauconitic quartz sandstone; shallow marine
Cuc **CLARKE SANDSTONE :** fossiliferous, red, glauconitic, feldspathic quartz sandstone, thin to medium cross-bedded; shallow marine
Cup **PRETLOVE SANDSTONE :** flaggy, cross-bedded and rippled, bioturbated quartz sandstone, siltstone; intertidal to shallow marine
Ems **SKEWTHORPE FORMATION :** flaggy, thinly cross-bedded and rippled sandstone, bioturbated siltstone, cross-bedded dolomitic sandstone and oolitic dolomite; stromatolitic; intertidal to shallow marine
Emh **HART SPRING SANDSTONE :** red, very fine to fine, micaceous quartz sandstone, thin to thick cross-bedded and thin parallel-bedded, rippled, unfossiliferous; tidal sand flats. Probable correlative of EAGLE HAWK SANDSTONE (Ord Basin)
Emt **TARRARA FORMATION :** siltstone with minor sandstone and fossiliferous oncolitic dolomite; shallow marine

CAMBRIAN — LATE — PAYTONIAN –IDAMEAN

MINDYALLAN

BOOMERANGIAN –TEMPLETONIAN

MIDDLE CAMBRIAN — ORDIAN

ORD BASIN

Goose Hole Group

Elder Subgroup
Eur **OVERLAND SANDSTONE :** white, clayey, lithic arkose, medium to thick cross-bedded, minor laminated; fluvial (southern sheet only)
Emb **EAGLE HAWK SANDSTONE :** red, fine, micaceous feldspathic sandstone, thin to medium cross-bedded, parallel-bedded, minor siltstone; tidal sand flats and possible fluvial. Probable correlative of HART SPRING SANDSTONE (Bonaparte Basin)

En **Negri Subgroup :** undifferentiated (southern sheet only)
Emp **PANTON FORMATION :** siltstone, lesser flaggy arkosic sandstone and mudstone, minor limestone; fossiliferous; intertidal and shallow marine
Emc **Corby Limestone Member :** grey, fine-grained micritic limestone with chert nodules; unfossiliferous; probably intertidal
Emd **Shady Camp Limestone Member :** fossiliferous oncolitic limestone; shallow marine
Eml **LINNEKAR LIMESTONE :** Lower : laminated, fine-grained micritic limestone with chert nodules and stromatolites Middle : grey-olive trilobitic shales. Upper : fossiliferous flaggy limestone and shale; probably intertidal to shallow marine
Emo **NELSON SHALE :** purple siltstone and mudstone, minor flaggy arkosic sandstone; intertidal
Emy **HEADLEYS LIMESTONE :** grey, laminated to massive, fine-grained micritic limestone with chert nodules and stromatolites; probably intertidal

EARLY CAMBRIAN

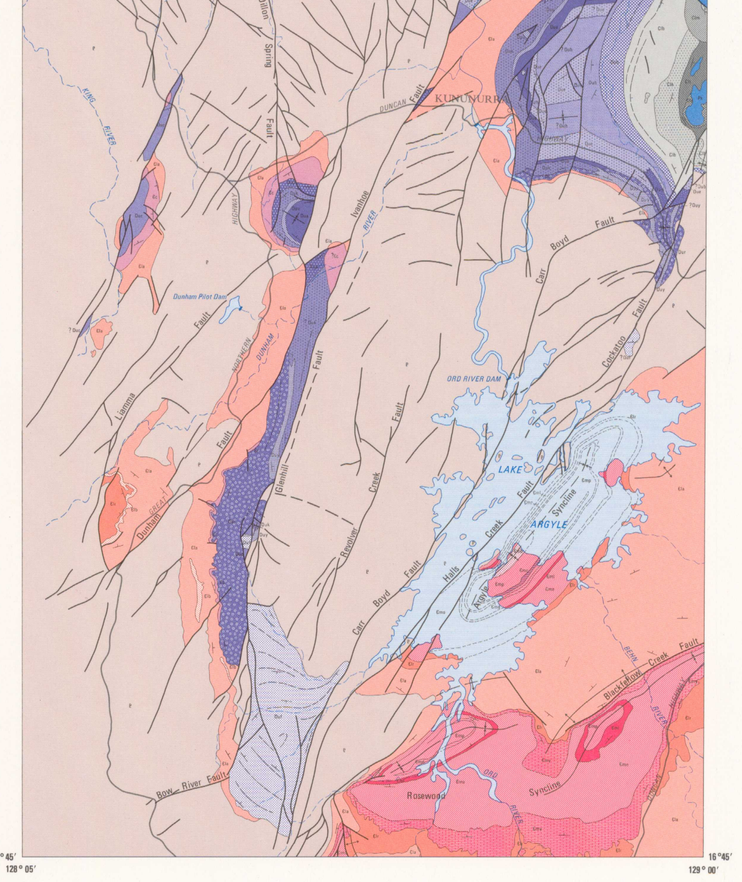
Ela **ANTRIM PLATEAU VOLCANICS :** massive, vesicular, amygdaloidal and porphyritic basalts with minor agglomerate, sandstone, tuff, siltstone and chert
Elr **Blackfella Rockhole Member :** fine-grained basalt and agglomerate
Elb **Bingy Bingy Member :** glomeroporphyritic basalt
Ela1 Unnamed, medium-grained, friable, cross-bedded sandstone; probably eolian

PROTEROZOIC

P Undifferentiated

For Symbols Panel see Plate 2

SOLID GEOLOGY



SCALE 1: 500 000

0 10 20 30 Kilometres

RELIABILITY DIAGRAM

A Detailed mapping
B1 Numerous traverses with air photo interpretation
B2 Air photo interpretation with a few traverses
C Air photo interpretation

HON. DAVID PARKER, M.L.A.
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D.R. KELLY, DIRECTOR GENERAL OF MINES

P.E. PLAYFORD
DIRECTOR, GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

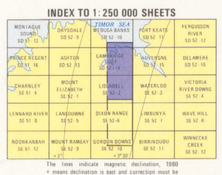
SCALE 1: 250 000

5000 0 5 10 15 20 25 30
Metres Kilometres

TRANSVERSE MERCATOR PROJECTION
ZONE 52 AUSTRALIAN MAP GRID

See Plate 2 for sections A–A', B–B', C–C'

INDEX TO 1:250 000 SHEETS



The lines indicate magnetic declination, 1980
+ means declination is east and correction must be added to compass bearing to give true bearing
— means declination is west and correction must be subtracted from compass bearing to give true bearing
Annual change in — 1' westerly

Geology by G.M. Beere and A.J. Mory 1980-82

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GEOLOGICAL MAP OF BONAPARTE AND ORD BASINS: NORTHERN SHEET

BONAPARTE AND ORD BASINS: SOUTHERN SHEET

SOLID GEOLOGY

SCALE 1 : 500 000

0 10 20 30 Kilometres

REFERENCE

CAINOZOIC — QUATERNARY

Qa Alluvium — sand, silt and clay

Czs Sand plain
Czb Black soil
Czl Lateritic soil
Czr Residual soil

CAINOZOIC — TERTIARY

Tp Laterite
Tf High level alluvium — poorly sorted clay, silt, sand and gravel
Tw **WHITE MOUNTAIN FORMATION** : marl, chert, siltstone; fossiliferous; lacustrine
Tl **LAWFORD BEDS** : chalcedonic limestone, chert, siltstone; lacustrine

ORD BASIN

LATE DEVONIAN — FRASNIAN

Mahony Group

Dd **GLASS HILL SANDSTONE** : medium to fine quartz arenite and minor pebbly sandstone, medium cross and parallel-bedded, minor siltstone; rare conglomerate; fluvial

Db **BOLL CONGLOMERATE** : red, pebble-boulder conglomerate, massive; pebbly sandstone and quartz arenite, medium to thick cross-bedded, minor parallel-bedded; minor siltstone; alluvial fan

Dc **PURRALILI SANDSTONE** : medium quartz arenite, well sorted, medium to thick planar cross-bedded, low angle cross-bedded, minor massive and parallel-bedded; eolian, fluvial

PALAEOZOIC — ? LATE CAMBRIAN — ? MINDYALLAN

Goose Hole Group

Elder Subgroup

Cor **OVERLAND SANDSTONE** : white, clayey, lithic arkose, medium to thick cross-bedded, minor laminated; fluvial

Cmb **EAGLE HAWK SANDSTONE** : red, fine, micaceous feldspathic sandstone, thin to medium cross-bedded, parallel-bedded, minor siltstone; tidal sand flats and possible fluvial. Probable correlative of HART SPRING SANDSTONE (Bonaparte Basin)

Cn **Negri Subgroup** : undifferentiated

CAMBRIAN — MIDDLE CAMBRIAN — BOOMERANGIAN –TEMPLETONIAN

Cmp **PANTON FORMATION** : siltstone, lesser flaggy arkosic sandstone and mudstone, minor limestone; fossiliferous; intertidal and shallow marine

Cmc **Corby Limestone Member** : grey, fine-grained micritic limestone with chert nodules; unfossiliferous; probably intertidal

Cmd **Shady Camp Limestone Member** : fossiliferous oncolitic limestone; shallow marine

CAMBRIAN — MIDDLE CAMBRIAN — ORDIAN

Cml **LINNEKAR LIMESTONE** : Lower : laminated, fine-grained micritic limestone with chert nodules and stromatolites. Middle : grey-olive trilobitic shales. Upper : fossiliferous flaggy limestone and shale; probably intertidal to shallow marine

Cmo **NELSON SHALE** : purple siltstone and mudstone, minor flaggy arkosic sandstone; intertidal

Cmy **HEADLEYS LIMESTONE** : grey, laminated to massive, fine-grained micritic limestone with chert nodules and stromatolites; probably intertidal

CAMBRIAN — EARLY CAMBRIAN

Cla **ANTRIM PLATEAU VOLCANICS** : massive, vesicular, amygdaloidal and porphyritic basalts with minor agglomerate, sandstone, tuff, siltstone and chert

Clr **Blackfella Rockhole Member** : fine-grained basalt and agglomerate

Clb **Bingy Bingy Member** : glomeroporphyritic basalt

Clc **Mount Close Chert Member** : laminated chert, intraformational breccia and stromatolites; possible hot water springs

Clm **Malley Spring Member** : siltstone and medium to coarse sandstone; possible eolian

PROTEROZOIC

P Undifferentiated

SYMBOLS

Geological boundary
- accurate
- inferred or concealed

Fault
- accurate
- inferred or concealed

Folds
- anticline; accurate, approximate
- syncline; accurate, approximate

Bedding
- inclined
- horizontal
- photo interpreted, dip < 5°
- dip 5° – 15°
- dip 15° – 45°
- trend line showing dip

Joint pattern

Lineaments
- probably reflecting underlying fault
- from air magnetics

Localities
- type section
- macrofossil
- vertebrate fossil
- spore occurrence
- trace fossil
- stromatolite

Petroleum exploration well
- abandoned, dry
- abandoned, show of gas

Crypto explosion structure (southern sheet)

Opencut mine — Ba
Alluvial deposit, not being worked or abandoned
Prospect or small mine — Ob
Mineral exploration drill hole — Cb
Down hole stratigraphy — Cu
Minor mineral occurrence — Di
- Barite
- Bitumen (in mineral exploration holes)
- Coal
- Copper
- Diamond
- Glauconite
- Iron
- Lead
- Uranium
- Zinc

Gl Fe Pb U Zn

Highway with national route marker
Formed road
Track
Townsite, pop. 1 000 – 10 000 — ○KUNUNURRA
Settlement, pop. less than 1 000 — • Turkey Creek
Homestead — ■ Nicholson
Yard
Airfield
Landing ground
Horizontal control; major, minor

Sand dunes

Watercourse; permanent, seasonal
Bore, dry bore — •B ⊘S
Well — •W
Spring — •S
Waterhole, pool — •WH •P
Rockhole — •RH
Tank — □T
Earth tank or dam — □E D
Windpump
Mineral drillhole, flowing artesian water — (DH)
Pump engine — (DHD)
Abandoned — (BBD)
Position approximate — (PA)

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D.R. KELLY, DIRECTOR GENERAL OF MINES

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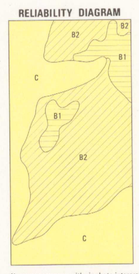
DIRECTOR, GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

SCALE 1: 250 000

5000 0 5 10 15 20 25 30 Kilometres
Metres

TRANSVERSE MERCATOR PROJECTION
ZONE 52 AUSTRALIAN MAP GRID

RELIABILITY DIAGRAM



B1 Numerous traverses with air photo interpretation
B2 Air photo interpretation with a few traverses
C Air photo interpretation

Geology by G.M. Beere and A.J. Mory 1980-82

Cartography by the Mapping Branch, Department of Mines, W.A.
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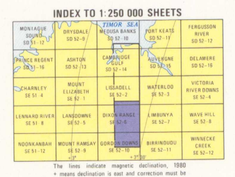
INDEX TO 1:250 000 SHEETS



The lines indicate magnetic declination, 1980
+ means declination is east and correction must be added to compass bearing to give true bearing
– means declination is west and correction must be subtracted from compass bearing to give true bearing
Annual change is – 1' westerly

DIAGRAMMATIC SECTION A–A′ (PLATE 1)

Vertical exaggeration x 3

DIAGRAMMATIC SECTION B–B′ (PLATE 1)

Vertical exaggeration x 3

DIAGRAMMATIC SECTION C–C′ (PLATE 1)

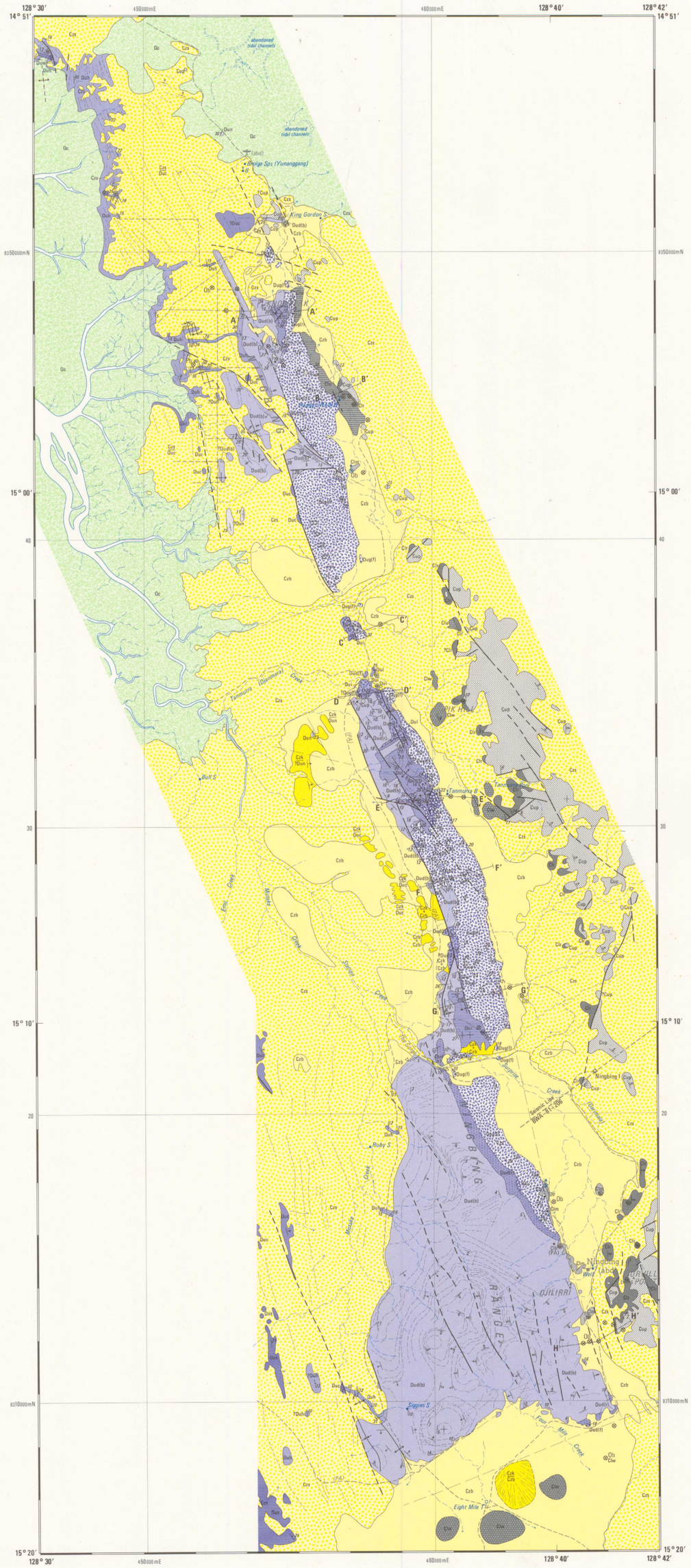
Vertical exaggeration x 3

DIAGRAMMATIC SECTION D–D′ (PLATE 2)

Vertical exaggeration x 3

GEOLOGICAL MAP OF BONAPARTE AND ORD BASINS: SOUTHERN SHEET

NINGBING RANGE



SCALE 1 : 100 000

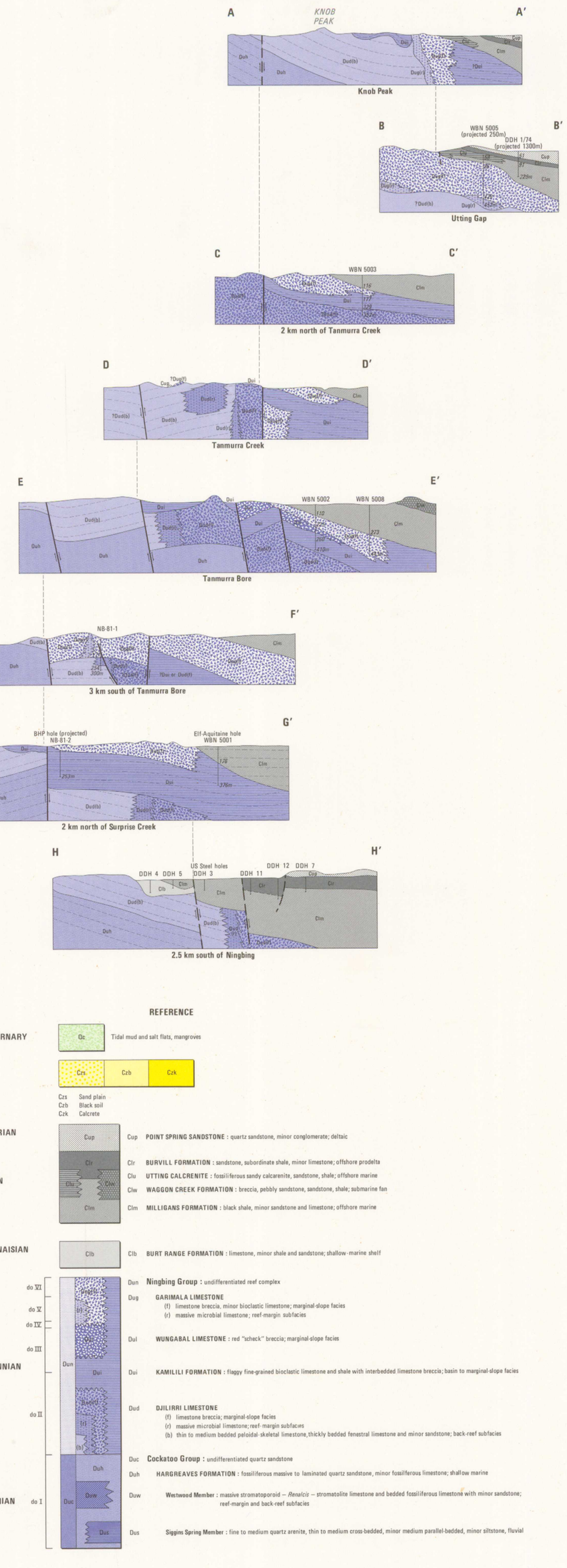
2000 0 2 4 6

Metres Kilometres

SECTIONS

SCALE 1 : 25 000

0 1000 Metres



REFERENCE

CAINOZOIC — QUATERNARY

Qc — Tidal mud and salt flats, mangroves

Czs Czb Czk

Czs — Sand plain
Czb — Black soil
Czk — Calcrete

CARBONIFEROUS

NAMURIAN / VISEAN

Cup — **POINT SPRING SANDSTONE** : quartz sandstone, minor conglomerate; deltaic

Clr — **BURVILL FORMATION** : sandstone, subordinate shale, minor limestone; offshore prodelta

Clu — **UTTING CALCRENITE** : fossiliferous sandy calcarenite, sandstone, shale; offshore marine

Clw — **WAGGON CREEK FORMATION** : breccia, pebbly sandstone, sandstone, shale; submarine fan

Clm — **MILLIGANS FORMATION** : black shale, minor sandstone and limestone; offshore marine

TOURNAISIAN

Clb — **BURT RANGE FORMATION** : limestone, minor shale and sandstone; shallow-marine shelf

LATE DEVONIAN

Dun — **Ningbing Group** : undifferentiated reef complex

FAMENNIAN

Dug — **GARIMALA LIMESTONE**
(f) limestone breccia, minor bioclastic limestone; marginal-slope facies
(r) massive microbial limestone; reef-margin subfacies

Dul — **WUNGABAL LIMESTONE** : red "scheck" breccia; marginal-slope facies

Dui — **KAMILILI FORMATION** : flaggy fine-grained bioclastic limestone and shale with interbedded limestone breccia; basin to marginal-slope facies

Dud — **DJILIRRI LIMESTONE**
(f) limestone breccia; marginal-slope facies
(r) massive microbial limestone; reef-margin subfacies
(b) thin to medium bedded peloidal-skeletal limestone, thickly bedded fenestral limestone and minor sandstone; back-reef subfacies

FRASNIAN

Duc — **Cockatoo Group** : undifferentiated quartz sandstone

Duh — **HARGREAVES FORMATION** : fossiliferous massive to laminated quartz sandstone, minor fossiliferous limestone; shallow marine

Duw — **Westwood Member** : massive stromatoporoid – *Renalcis* – stromatolite limestone and bedded fossiliferous limestone with minor sandstone; reef-margin and back-reef subfacies

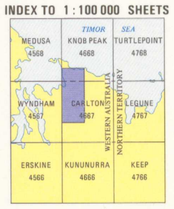
Dus — **Siggins Spring Member** : fine to medium quartz arenite, thin to medium cross-bedded, minor medium parallel-bedded, minor siltstone, fluvial

SYMBOLS

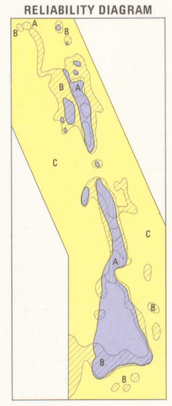
- Geological boundary
  - accurate
  - inferred or concealed
- Fault
  - accurate
  - inferred or concealed
- Folds
  - syncline showing plunge
  - anticline
- Bedding
  - inclined
  - horizontal
  - photo interpreted, dip <5°
  - dip 5° – 15°
  - dip 15° – 45°
- trend line
- Joint pattern
- Lineament, probably reflecting underlying fault
- Localities
  - type section
  - macrofossil
  - vertebrate fossil
  - stromatolite
- Petroleum exploration well, dry, abandoned
- Mineral exploration drill hole
  - with water flow
- Track
- Homestead — Ningbing
- Landing ground
- Watercourse
- Bore with windpump
- Spring
- Earth tank or dam
- Abandoned (abd)
- Position approximate (PA)
- Minor mineral occurrence
  - Bitumen Ob
  - Lead Pb
  - Zinc Zn

LOCALITY MAP

INDEX TO 1 : 100 000 SHEETS



RELIABILITY DIAGRAM



A Detailed mapping
B Traverses with air photo interpretation
C Air photo interpretation
Outcrop of Ningbing Group

Geology : Devonian A J Mory 1980-82
Carboniferous G M Beere 1980-81

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DEVONIAN AND CARBONIFEROUS GEOLOGY OF NINGBING RANGE — BONAPARTE BASIN