GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 133

GEOLOGY OF THE CARNARVON BASIN WESTERN AUSTRALIA

BY

R. M. HOCKING, H. T. MOORS,
AND W. J. E. VAN DE GRAAFF

DEPARTMENT OF MINES
WESTERN AUSTRALIA

GEOLOGY OF THE CARNARVON BASIN
WESTERN AUSTRALIA

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FRONTISPIECE

Murchison River gorge at the Z Bend, looking northeast. The gorge cuts through strongly bedded, Silurian Tumblagooda Sandstone, the oldest known unit of the Carnarvon Basin succession. The steep-sided gorge is flanked by a broad, gently sloping valley, which rises in turn to a relatively featureless, lateritized plateau: the Victoria Plateau. Lower Cretaceous marine sediments locally rest on the sides of the upper valley, below plateau level. This suggests that the valley formed in the Jurassic or earliest Cretaceous, and was later drowned. Incision of the central gorge took place in the late Tertiary and Quaternary, after lateritization of the Victoria Plateau and parts of the upper valley.

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by

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SUMMARY

The Carnarvon Basin is an epicratonic, faulted and gently folded, Phanerozoic basin which spans 1000 km of the west and northwest coast of Western Australia. It is elongated north-south, and is transitional southwards into the Perth Basin and northeastwards into the offshore Canning Basin. Precambrian rocks flank the basin on the east. The total area to the continental/oceanic crust boundary is 650 000 km^2.

In the southern (largely onshore) portion of the basin, sub-basins are broadly north-trending, have a northerly and northwesterly tectonic fabric, and contain up to 7 km of Palaeozoic sediments, with a Mesozoic veneer which thickens northwards and westwards. In the northern (largely offshore) portion, sub-basins trend northeastwards, have a northeasterly and easterly tectonic fabric, and contain thick Mesozoic sequences. Total sediment thickness is up to 15 km.

In the Palaeozoic, deposition occurred in a broad, north-opening trough, the eastern half of which is preserved as the onshore portion of the Carnarvon Basin. The basin was initially an interior fracture basin in the Silurian, and developed into an interior sag basin in the Devonian.

The major phases of deposition, and the sequences produced by them, are outlined below.

1. Silurian to Early Devonian — continental sandstone to shallow-marine carbonate with evaporites. The sequence is up to about 5 km thick and was deposited in two tectonically caused megacycles.

2. Middle Devonian to Early Carboniferous — shallow-marine carbonate, with fault-related continental and shallow-marine sandstone and conglomerate near the basin margin. A possible hiatus at the Devonian-Carboniferous boundary divides the sequence into a Devonian portion, about 1500 m thick, and a Lower Carboniferous portion about 600 m thick.

3. Late Carboniferous to early Late Permian — fluvial to marine-shelf sandstone, siltstone and shale with lesser carbonate. About 3 km of glacial and postglacial siliciclastics with lesser carbonate, below, are separated from about 2.5 km of deltaic to marine-shelf sandstone and shale, above, by an early Artinskian erosional hiatus. This was the last significant deposition in the onshore Carnarvon Basin.

In the Mesozoic, depocentres shifted to northeast-trending sub-basins with active faulting. These lay to the north of the Palaeozoic depocentres, mostly in the offshore part of the Carnarvon Basin. They developed in response to stresses produced by the breakup of Gondwana, which here took place in the mid-Jurassic. Deposition was in pre-rift and rift-interior fracture basins prior to the Callovian, and in post-rift marginal-sag basins afterwards.

4. Latest Permian to Early Jurassic — marine and fluviodeltaic sandstone and shale. Rapid subsidence in the northern Carnarvon Basin formed a transgressive-regressive couplet more than 3 km thick. In some areas, a second, thinner couplet spans the Jurassic-Triassic boundary. A veneer of Lower Triassic sediments also extends into the southernmost Carnarvon Basin from the Perth Basin.

5. Early Jurassic to earliest Cretaceous — marine siltstone and sandstone. After a widespread transgression, abundant supply (coupled with syndepositional faulting) resulted in a siltstone-dominated sequence more than 4 km thick. Marine and continental sandstone were deposited locally. A Callovian unconformity related to Gondwana breakup divides the sequence in most areas.

6. Early to Late Cretaceous siliciclastic deposition — fluviodeltaic and shallow-marine sandstone to shale (up to 1200 m thick), overlain by siliceous chemical deposits and siltstone (up to about 1000 m thick). A mid-Neocomian hiatus separates them.

7. Late Cretaceous carbonate deposition — marine-shelf and continental-slope limestone, marl, and claystone. The sequence is up to 1 km thick, and resulted from changed oceanic circulation patterns following Gondwana breakup.

Major Cainozoic deposition occurred only in the northern Carnarvon Basin with a veneer elsewhere, resulting in northwestwards progradation of the continental shelf. The phases are distinguished largely by the unconformities which separate them. The thickness of sediment deposited in each phase shows marked areal variation.

8. Early Paleocene to Early Eocene — marine shelf and slope carbonate and claystone. Most of the onshore part of the basin was emergent.

9. Middle to Late Eocene — marine shelf and slope carbonate, extending south approximately along the present coastline. A veneer of shallow-marine to fluvial sands extends on to the central, onshore portion of the basin.

10. Late Oligocene to Late Miocene — marine shelf and slope carbonate, with local emergent shoals of quartz sand. In onshore areas a widespread veneer, of fluvial and residual sandstone and conglomerate, developed. Extensive duricrust formation occurred in the Oligocene and, further south, in the Miocene.

11. Late Miocene to ?Holocene. Marine, carbonate-dominated deposition occurred in presently offshore areas, with erosion or eolian reworking and deposition elsewhere. Eolian calcarenite more than 300 m thick accumulated along the Zuytdorp Cliffs. Thinner eolian sequences flanked Cape Range and draped over other developing coastal anticlines.

The northern Carnarvon Basin contains the Barrow Island and Harriet oil fields, North Rankin gas field, and several other significant gas and oil accumulations, most of which are offshore. The main sources and reservoirs are Triassic or Lower Cretaceous, with Lower Cretaceous seals.

Coal exploration has centred on the Permian Wooramel Group. Despite extensive exploration, only thin seams have been found, generally at depths too great for exploitation. They are not economic.

Sediment-hosted uranium mineralization has been found in several areas, within Permian and Lower Cretaceous hosts. A Lower Cretaceous palaeochannel system near the Ashburton River is marginally economic. Several uranium prospects remain for future exploration. There has been very little exploration for base metals, but much of the Palaeozoic sequence appears prospective. Several other commodities are either known within, or extracted from, the Carnarvon Basin. These include evaporites, heavy-mineral sands, garnet sand, limestone, bentonite, barite, phosphate, and attapulgite. Extensive supplies of stock-quality groundwater occur in Palaeozoic, Mesozoic and Cainozoic sediments. But potable groundwater is generally restricted to certain stratigraphic units and along the courses of major rivers. Artesian or subartesian water is available in most of the area of Mesozoic outcrop or subcrop.

CHAPTER 1

Introduction

LOCATION

The Carnarvon Basin is an elongate basin along the western and northwestern coastline of Western Australia between Geraldton and Karratha, a distance of about 1000 km (Fig. 1). South of 23°S it is dominantly north-trending, but to the north the orientation swings around and north of 22°S it trends northeast.

The width of the basin onshore ranges from about 50 to 300 km, but is generally 150 to 200 km. Offshore, it extends at least as far as the Exmouth Plateau, more than 400 km from the eastern basin margin. Sediments usually extend to the continental/oceanic crust boundary, and the offshore boundary of the Carnarvon Basin is placed somewhat arbitrarily at the 2000 m bathymetric contour. This gives an onshore area of 115 000 km^2 and an offshore area of about 535 000 km^2. The bulletin deals primarily with the area shorewards of the 200 m bathymetric contour. The onshore Carnarvon Basin covers all or part of the fourteen 1:250 000 geological maps shown in Figure 1.

SETTLEMENT, CLIMATE AND VEGETATION

The Carnarvon Basin is covered by pastoral leases except for large areas of vacant land on YARINGA* and AJANA, Kalbarri National Park (on AJANA) and Cape Range National Park (on YANREY–NINGALOO and ONSLOW). In addition, much of the Kennedy Range has been proposed for gazettal as a national park. The pastoral leases are mostly sheep stations, with cattle grazing on some leases. There is a network of station tracks of varying quality, and station homesteads are linked to main roads by formed gravel roads. All gravel roads are subject to closure in wet weather. The only bitumen roads (in 1984) are the North West Coastal Highway, the roads linking Kalbarri, Denham and Exmouth with the highway, and some roads in the extreme south of the basin on GERALDTON. The only large town in the basin is Carnarvon (pop. 5053), although Karratha (pop. 8341) is just to the northeast and Geraldton (pop. 20 895) is just to the south. Kalbarri (pop. 820), Gregory, Denham (pop. 402), Useless Loop, Gascoyne Junction, Exmouth (pop. 2583) and Onslow (pop. 594) are smaller towns or settlements, and several roadhouses are located along the North West Coastal Highway (Bartlett, 1983). A Royal Flying Doctor Service base in Carnarvon, provides a radio service to those stations without a telephone. The Dampier-Perth Natural Gas Pipeline passes down the eastern side of the Carnarvon Basin.

The climate is semi-arid to arid, with average annual rainfall between 200 and 300 mm, increasing to 400 mm south of Kalbarri. Potential annual evaporation ranges between about 2000 and 3500 mm, increasing inland. Temperatures are warm to hot, with average daily maximum temperatures ranging from about 30°C to 37°C in summer and from about 20°C to 24°C in winter, and minimum temperatures of about 20°C to 23°C in summer and 11°C to 14°C in winter. Most rainfall is in winter, although summer rains increase in importance north of Carnarvon.

Details of the flora and fauna of the Carnarvon Basin were given by Ride and others (1974). Beard produced 1:250 000 vegetation maps of GERALDTON, AJANA and SHARK BAY–EDEL (Beard, 1976a, 1976b, 1976c), 1:1 000 000 vegetation maps of the Pilbara and Murchison areas (Beard, 1975, 1976d), and a general map and review of the vegetation of Western Australia (Beard, 1981). Most of the Carnarvon Basin is covered by open to dense shrub-steppe vegetation, dominated by hummock grassland, or spinifex north of Carnarvon. South of the Gascoyne River, acacia scrub is dominant, and south of Shark Bay, mallee heath is dominant. Soils in the area were briefly described by Northcote (1967).

* 1:250 000 map sheet names are printed in capitals to distinguish them from place names.

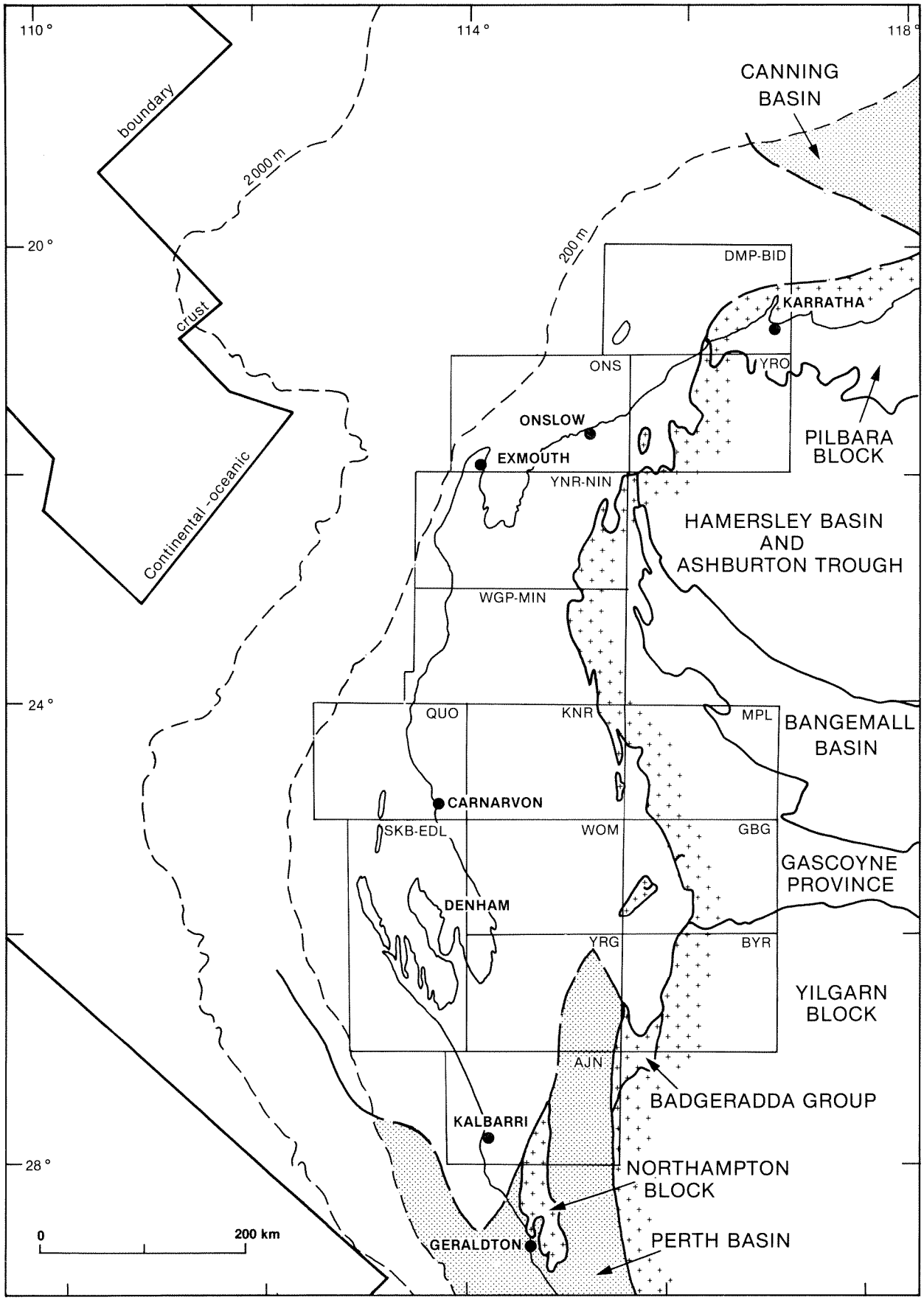

Figure 1. **Location of Carnarvon Basin, adjacent tectonic units, and 1:250 000 geological sheets. AJN, Ajana: YRG, Yaringa: BYR, Byro: GBG, Glenburgh: WOM, Wooramel: SKB–EDL, Shark Bay–Edel: QUO, Quobba: KNR, Kennedy Range: MPL, Mount Phillips: WGP–MIN, Winning Pool–Minilya: YNR–NIN, Yanrey–Ningaloo: YRO, Yarraloola: DMP–BID, Dampier–Barrow Island.**

PRESENT INVESTIGATION

The present study commenced in 1975 with the mapping of YANREY–NINGALOO and ONSLOW, and a geophysical study of the Carnarvon Basin by M. N. Megallaa. Numerous personnel were involved in the mapping, which concluded in 1979 and embraced all, or part of, twelve of the fourteen map sheets covering the Carnarvon Basin. These personnel and their period of involvement are listed in Table 1. Further fieldwork specifically for this bulletin was done by R. M. Hocking and H. T. Moors in 1980. Results of fieldwork in 1982 by R. M. Hocking for a separate project have also been incorporated.

Other publications which have directly resulted from the present study are by Allen (in press); Cockbain (1980, 1981, 1985); Denham and van de Graaff (1977); Grey and others (1977); Harrison (1985); Hocking (1979, 1981, 1985); Hocking and others (1980); Hocking and van de Graaff (1978); Lavaring (1979); Megallaa (1980); Moore, Denman and Hocking (1980); Moore and Hocking (1983); Moore, Hocking and Denman (1980); Moors (1980, 1981a); van de Graaff (1981); van de Graaff and others (1976), and van de Graaff, Hocking and Denman (1977). Moors (1981b) compiled a geological bibliography of the Carnarvon Basin to 1980.

In this bulletin, R. M. Hocking wrote most of the text dealing with the onshore part of the Carnarvon Basin, compiled all maps and integrated all the text. H. T. Moors wrote most of the text dealing with the northern, offshore part of the basin and the petroleum geology. W. J. E. van de Graaff wrote a major internal GSWA report from which the physiography section is derived. In addition, his ideas are reflected in a large part of the sedimentology herein. Parts of this bulletin were prepared by P. H. Harrison, A. D. Allen (Geological Survey of Western Australia), R. S. Heath and M. C. Apthorpe (Woodside Offshore Petroleum Pty Ltd), and A. M. Tait and D. N. Smith (West Australian Petroleum Pty Ltd). The Geological Survey personnel listed in Table 1 have made significant contributions towards the understanding of all or part of the Carnarvon Basin. In much of this bulletin the ideas presented are a consensus of those opinions. Particular mention must be made of M. H. Johnstone, who provided invaluable background information and general knowledge, and assisted in the compilation of the pre-Cretaceous map (Plate 2).

PREVIOUS INVESTIGATIONS

Apart from a few reconnaissance traverses, the only geological work in the Carnarvon Basin until the 1920s was by A. Gibb Maitland of the Geological Survey of Western Australia. Since the 1920s, the main incentives for investigation have been the searches for hydrocarbons and artesian water, but recently other minerals such as uranium, coal and diamonds have been exploration targets. Until the early 1950s the basin was called the North West Basin. The term Carnarvon Basin was first used by Gentilli and Fairbridge (1951).

Hydrocarbon exploration commenced in 1924 when a Sydney business man, Mr. A. E. Broue, hired an experienced American petroleum consultant, F. G. Clapp. He produced a very pessimistic report, which disclaimed any chance of commercial accumulations (Clapp, 1925, 1926a, 1926b). In 1929, Oil Search Limited began investigations in the basin. The initial traverses immediately indicated that the basin held much brighter hydrocarbon prospects than suggested by Clapp, but after intensifying its effort, the company relinquished all prospecting rights in 1934 without drilling a well. Major papers which resulted from this venture are by Condit (1935), Condit and others (1936) and Raggatt (1936).

In 1947, the Australian company AMPOL took up exploration permits which included all of the onshore Carnarvon Basin. It commissioned a number of American consultants to compile reports on the permits, and in conjunction with Caltex formed West Australian Petroleum Pty Ltd (WAPET) in 1951. With American capital and expertise, WAPET instigated a serious exploration program, employing the first contract seismic crew in Australia in 1952. Several prospects were outlined and in 1953 WAPET's first well, Rough Range 1, struck the first flowing oil in Australia's history (Johnstone, 1979). This unfortunately proved to be uncommercial but provided impetus for continued exploration in the Carnarvon Basin.

A detailed study of the Carnarvon Basin by the Bureau of Mineral resources (BMR) also began in 1947. In 1948 the first field party, (under the leadership of Curt Teichert) was immediately successful in extending the known stratigraphic column in the Carnarvon Basin by establishing the presence of pre-Permian sediments. Surface samples were collected and sent to the Commonwealth Scientific and Industrial Research Organization (CSIRO), and a report on them was produced (Edwards, 1952). Fieldwork continued until 1956, (under the leadership of M.A. Condon from 1949 onwards) and numerous reports and

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papers ensued. These included the following: a preliminary description of the geology of the Carnarvon Basin by Condon (1954); reports on specific areas by Condon and others (1953, 1955, 1956), Konecki and others (1958) and Perry and Dickins (1960); explanatory notes by Condon (1955, 1962a, 1962b, 1965a); and numerous palaeontological reports. Concurrently with the mapping, BMR geophysicists conducted gravity and magnetic surveys and shot a number of seismic-reflection surveys (Chamberlain and others, 1954), which showed that the Carnarvon Basin extended offshore. As a result of the mapping, the BMR drilled five stratigraphic wells in the Carnarvon Basin (Bastian and Willmott, 1965; Perry, 1965; Mercer, 1967). The BMR study culminated in the bulletin by Condon (1965b, 1967, 1968), which described the onshore Carnarvon Basin in detail.

In 1963 Woodside (Lakes Entrance) Oil N.L.* applied for the contiguous offshore permit areas to WAPET, and these two companies then held title (for a short time) to the whole of the Carnarvon Basin. Both pursued vigorous exploration programs and discovered oil on Barrow Island (WAPET) and gas on the North West Shelf (Woodside). The history of exploration of these two companies was summarized by Raggatt (1964), Thomas and Smith (1974, 1976), Powell (1976a), Martinson and others (1973), Thomas and others (1978), Crank (1973), and Johnstone (1979). The interested reader is referred to these for further details.

In the mid 1970s, improved technology made investigation of the Exmouth Plateau feasible, and this was the next major phase of exploration in the Carnarvon Basin. Details of the exploration are contained in Exon and Willcox (1978, 1980) and Wright and Wheatley (1979).

Although the BMR and oil companies dominate the history of investigation of the Carnarvon Basin, the Geology Department of the University of Western Australia has also been very active. Firstly, C. Teichert led research about the time of World War 2 when there was no other activity in the Carnarvon Basin. Secondly, since about 1964 a marine research group under the leadership of B. Logan has been studying Quaternary coastal sedimentary processes, mostly in the Shark Bay, Lake MacLeod and Exmouth Gulf areas. Two major reports have arisen from this study: Logan, Davies and others (1970) and Logan, Read and others (1974). In addition, there have been several honours and postgraduate studies in the Carnarvon Basin.

General summaries of the Carnarvon Basin, utilizing BMR, oil company and other data, have been written by McWhae and others (1958), Thomas and Smith (1974, 1976), Playford and others (1975) and Johnstone and others (1976).

OVERVIEW

BOUNDARIES

The boundaries of the Carnarvon Basin and its sub-basins have been defined using presently expressed structural and physiographic elements. Each basin is "an area which is underlain by a substantial thickness of sedimentary rocks and which exhibits certain unifying characteristics of stratigraphy and structure" (Playford and others, 1975, p. 224). This is in contrast with a stratigraphically and sedimentologically (palaeogeographically) based definition, in which genetically and chronologically related sequences were deposited, and which may overlie and onlap other basins. The sub-basins are shown in Figure 2, and the stratigraphy is summarized in Figure 3. Tectonic units adjoining the Carnarvon Basin are shown in Figure 1.

In the north, the Carnarvon Basin is transitional (offshore) to the Canning Basin. Although the Beagle Sub-basin was included in the Carnarvon Basin by Robertson and others (1978) and Powell (1982), we follow Playford and others (1975) in regarding the De Grey Nose as the northeastern boundary. The Carnarvon Basin is bounded to the east by the Precambrian craton and, following Playford and others (1975, 1976), the southern boundary of the Carnarvon Basin is taken to be along the faulted western contact of the Precambrian Northampton block and its north-northeastwards extension — the Ajana Ridge and Fault System. This places the Coolcalalaya Sub-basin in the Perth Basin although there is no evidence that separate depositional basins existed in the Palaeozoic. Offshore, the Geelvink Fault separates the Carnarvon Basin to the north from the Abrolhos Sub-basin and Turtle Dove Ridge of the Perth Basin to the south (Megallaa, 1980).

SUB-BASINS

The sub-basins of the Carnarvon Basin, shown in Figure 2, fall into two groups. The first group contains predominantly Palaeozoic sediments, trends northwards, and is largely restricted

* To avoid confusion, the Woodside consortium is hereafter referred to simply as "Woodside", although the name of the operating company has changed from time to time: BOC of Australia (1964-75), BOCAL Pty Ltd (1975-76), Woodside Petroleum Development Pty Ltd (1976-81), and Woodside Offshore Petroleum Pty Ltd (1982-present).

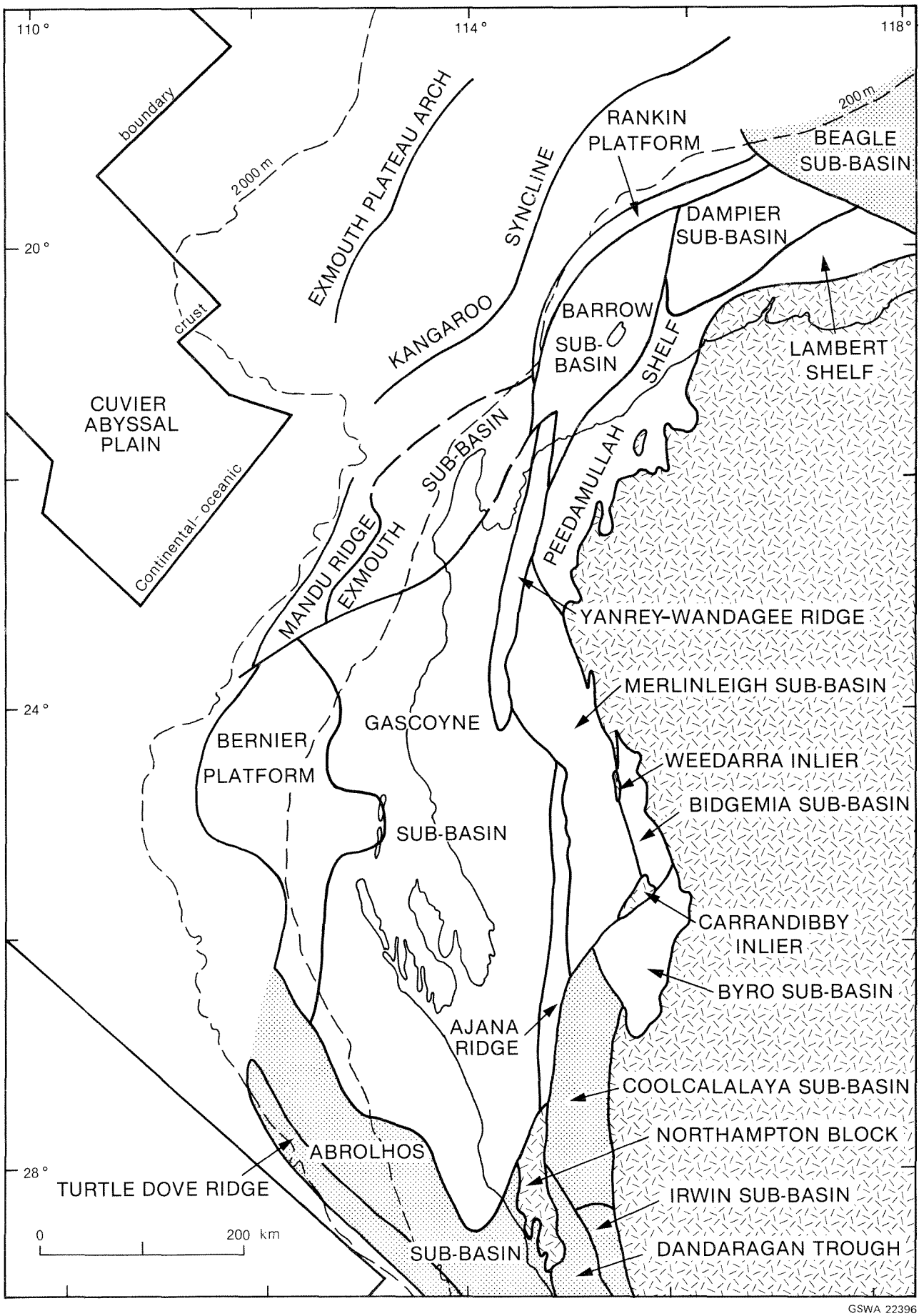
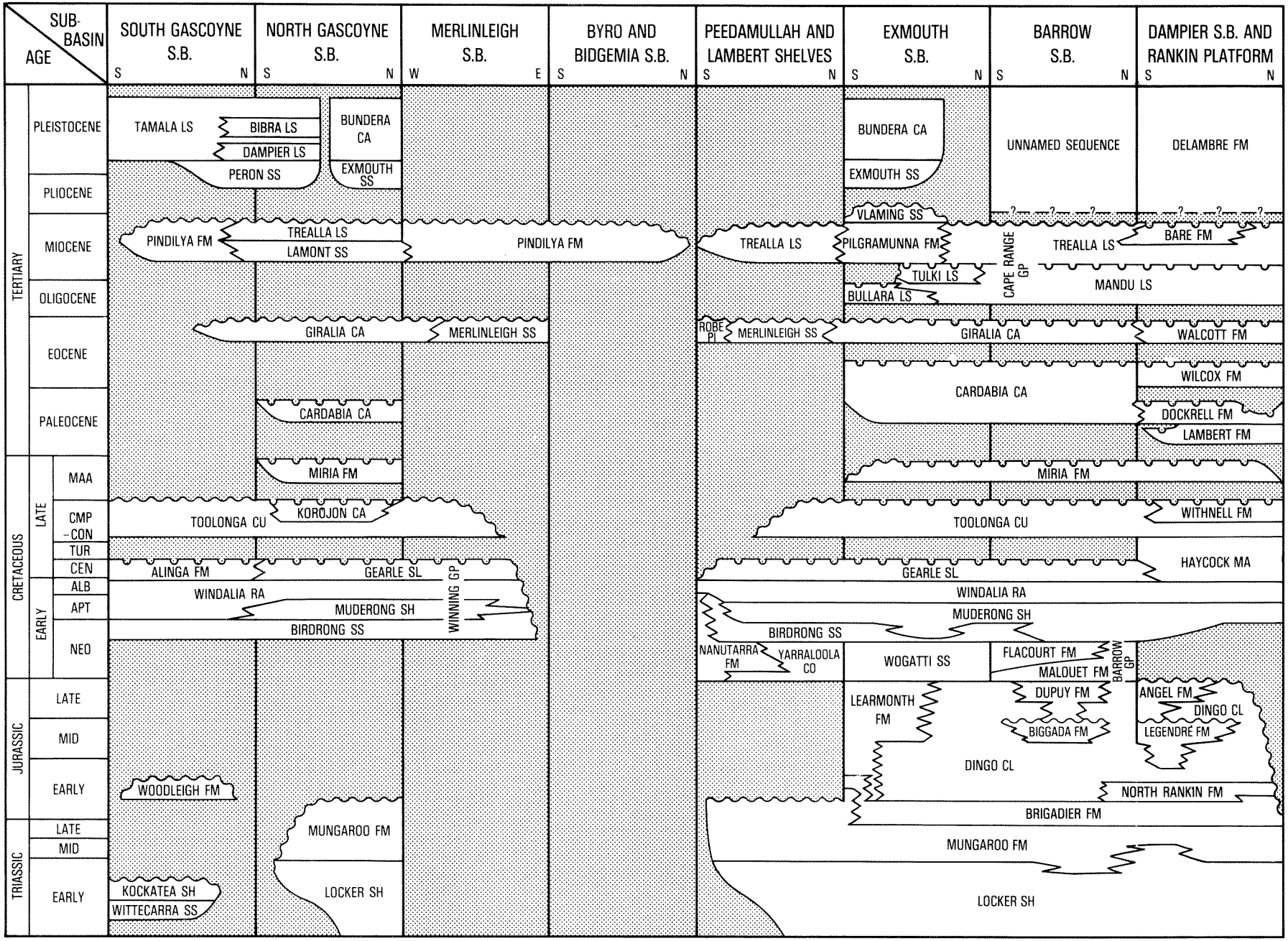


Figure 2. **Sub-basins and major tectonic units of the Carnarvon Basin. Following Exon and Willcox (1980), the Exmouth Plateau Arch and Kangaroo Syncline are included in the Carnarvon Basin.**


SUB-BASIN
AGE
SOUTH GASCOYNE S.B.
NORTH GASCOYNE S.B.
MERLINLEIGH S.B.
BYRO AND BIDGEMIA S.B.
PEEDAMULLAH AND LAMBERT SHELVES
EXMOUTH S.B.
BARROW S.B.
DAMPIER S.B. AND RANKIN PLATFORM
S N
W E
TERTIARY
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
CRETACEOUS
LATE
EARLY
MAA
CMP -CON
TUR
CEN
ALB
APT
NEO
JURASSIC
LATE
MID
EARLY
TRIASSIC
LATE
MID
EARLY
TAMALA LS
BIBRA LS
DAMPIER LS
PERON SS
BUNDERA CA
EXMOUTH SS
PINDILYA FM
TREALLA LS
LAMONT SS
GIRALIA CA
MERLINLEIGH SS
CARDABIA CA
MIRIA FM
TOOLONGA CU
KOROJON CA
ALINGA FM
GEARLE SL
WINNING GP
WINDALIA RA
MUDERONG SH
BIRDRONG SS
WOODLEIGH FM
MUNGAROO FM
LOCKER SH
KOCKATEA SH
WITTECARRA SS
UNNAMED SEQUENCE
DELAMBRE FM
VLAMING SS
BARE FM
PILGRAMUNNA FM
TULKI LS
BULLARA LS
CAPE RANGE GP
MANDU LS
ROBE PI
WALCOTT FM
WILCOX FM
DOCKRELL FM
LAMBERT FM
WITHNELL FM
HAYCOCK MA
NANUTARRA FM
YARRALOOLA CO
WOGATTI SS
FLACOURT FM
MALOUET FM
BARROW GP
DUPUY FM
BIGGADA FM
LEARMONTH FM
ANGEL FM
DINGO CL
LEGENDRE FM
NORTH RANKIN FM
BRIGADIER FM

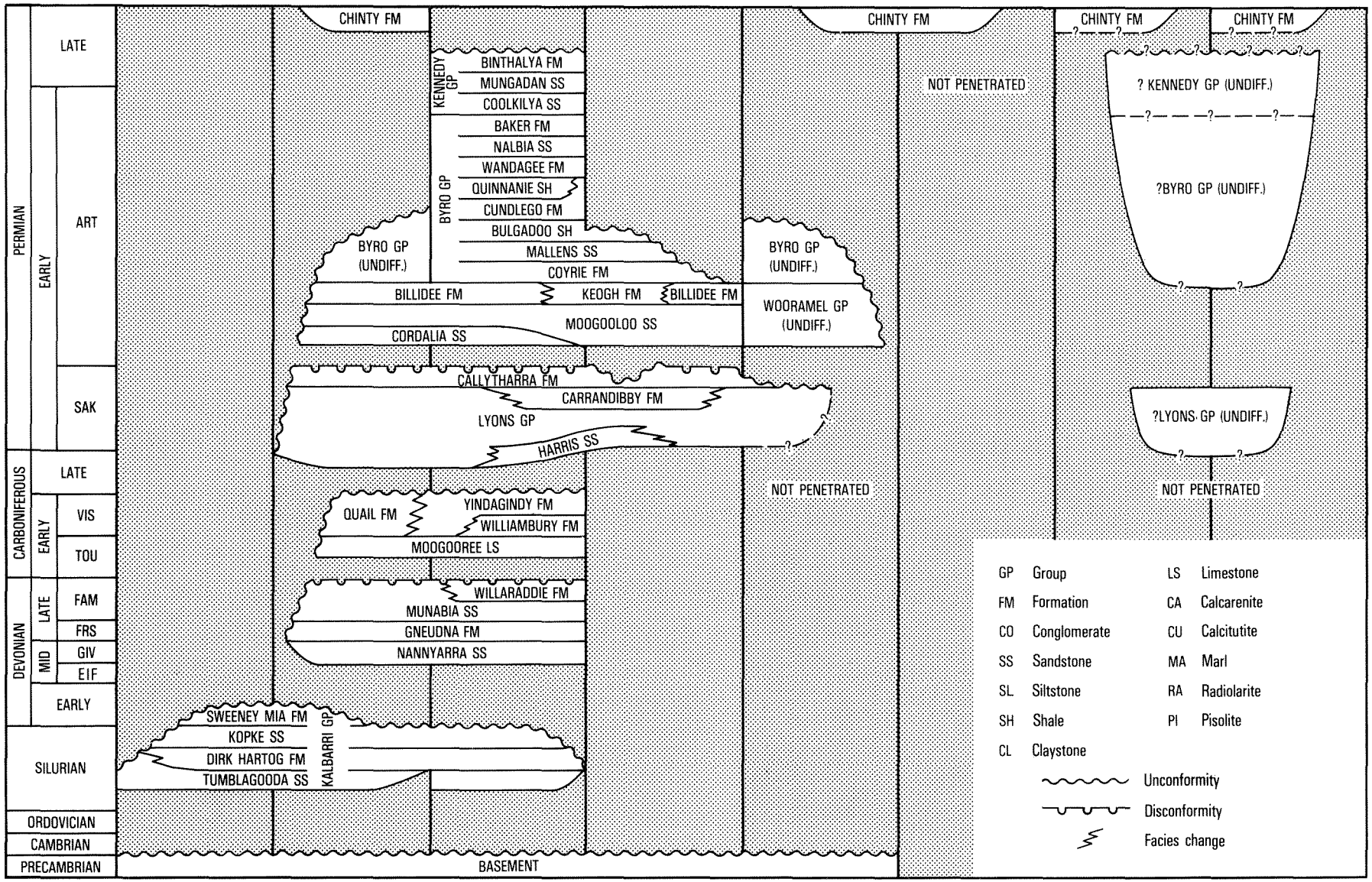


Figure 3. Generalized stratigraphy of the Carnarvon Basin. No linear vertical scale. Lateral and vertical relationships diagrammatic. See lower right hand of figure for abbreviations.

to onshore areas. The second group contains large thicknesses of Mesozoic and Cainozoic sediments, is mainly northeast trending, and forms the northern, mostly offshore, Carnarvon Basin.

The Byro, Bidgemia and Merlinleigh Sub-basins are primarily half-grabens containing mainly Upper Carboniferous and Permian sediments. Lower Carboniferous and Devonian sediments and a Cretaceous veneer are present in the northern part of the Merlinleigh Sub-basin, and Silurian sediments occur in the western part. Faults and basement ridges, which are largely post-depositional, separate the three sub-basins. Along these ridges, basement rocks are exposed in the Carrandibby and Weedarra Inliers. Thomas and Smith (1974, 1976) recognized the Ashburton Sub-basin between the Merlinleigh Sub-basin and the Peedamullah Shelf but, following Playford and others (1975), this area is here divided between the Merlinleigh Sub-basin and Peedamullah Shelf.

The Ajana and Wandagee-Yanrey Ridges separate the Merlinleigh Sub-basin from the Gascoyne Sub-basin, and in most areas are included in the Gascoyne Sub-basin as its easternmost part. The eastern boundary of the ridges is a series of major, down-to-the-east fault systems, which are poorly defined south of the Gascoyne River because of a lack of geological and geophysical data. The Gascoyne Sub-basin is a north-south elongated, uplifted and gently westwards tilted platform containing primarily Silurian and Devonian sediments with minor Carboniferous and Permian remnants and, in the Exmouth Gulf area, Triassic and Jurassic sediments. A westwards-thickening Cretaceous veneer mantles older sediments.

The Bernier Platform is a broad, offshore, north-south oriented area of shallow basement which forms the western boundary of the Gascoyne Sub-basin. A thin Palaeozoic sequence, overlain by Cretaceous and Cainozoic sediments, is present on the platform (Megallaa, 1980).

The Peedamullah and Lambert Shelves are areas of shallow basement with onlapping Mesozoic and Cainozoic deposits which thicken offshore. Palaeozoic sediments are present in the more westerly and northerly (deeper) parts of the Peedamullah Shelf. Both shelves have faulted boundaries with the Barrow and Dampier Sub-basins, respectively.

The Exmouth, Barrow and Dampier Sub-basins trend northeast, in contrast with the north-south orientation of the onshore sub-basins, and contain thick sequences of Mesozoic (primarily Jurassic and Cretaceous) and Cainozoic sediments. The thickness of the underlying Palaeozoic sequence is unknown. The Exmouth Sub-basin is separated from the Exmouth Plateau Arch, to the northwest, by the Kangaroo Syncline (sometimes referred to as the Kangaroo Trough). The Barrow and Dampier Sub-basins are faulted against the Rankin Platform to the north and northwest.

The Rankin Platform is a faulted, elongate horst complex of Mesozoic sediments which separates the grabens of the Dampier and Barrow Sub-basins from the Kangaroo Syncline. It is the most northwesterly structure discussed in detail in this bulletin. The southernmost extension of the platform is sometimes termed the Hilda-Alpha Arch.

Both the Kangaroo Syncline, (a broad synclinal structure northwest of the Exmouth Sub-basin and Rankin Platform) and the Exmouth Plateau Arch (a structurally high area seaward of the Kangaroo Syncline) contain a thick Mesozoic and Cainozoic sequence. They were considered to be part of the Carnarvon Basin by Exon and Wilcox (1978, 1980) and are not discussed in detail in this bulletin.

The sub-basins of the Carnarvon Basin are generally related to a plate-tectonic model and the breakup of Gondwana. The north-trending sub-basins initially developed as "failed arms" (Veevers, 1984). A Silurian rifting event triggered deposition along the west coast, and was followed by gradually decreasing tectonism, subsidence and deposition in the Devonian and Carboniferous. In the Late Carboniferous and Permian, the sub-basins developed into pre-breakup, or "infrarift", basins (Falvey and Mutter, 1981).

In the Triassic, tectonic arching of the north-trending sub-basins occurred and a pronounced infrarift basin developed in the northern Carnarvon Basin. This basin was closely related to the impending Jurassic breakup (at 160 Ma) along the northwest Australian margin, and in the Jurassic developed into the northeast-trending rift valley sub-basins. Major fault movements associated with breakup occurred both onshore and offshore in the Jurassic, and fully delineated the present sub-basins. These movements had largely ceased by the Cretaceous, and the sub-basins developed first into rim basins (Veevers and others, 1982) and then into post-breakup, trailing-edge basins.

SEDIMENTARY SEQUENCE

The Carnarvon Basin contains sediments ranging in age from Silurian to Holocene (Fig. 3). The Proterozoic Badgeradda Group (considered to

be part of the Carnarvon Basin sequence by Condon, 1965b) and the Uaroo Group are omitted from this bulletin because we consider that they are related to a different phase of deposition, with different structural and sedimentological controls. Palaeozoic sedimentation took place in continental to marine-shelf environments. The continental deposits consist of siliciclastic, braided-fluvial and (in areas near the basin margin) alluvial-fan deposits. Marine deposits consist of siliciclastic and carbonate, shoreline, near-shore and marine-shelf deposits. Red beds and evaporitic sediments, deposited in two major cycles totalling more than 4000 m thickness, dominate the Silurian sequence. The Devonian and Lower Carboniferous sequences consist of more than 2000 m of braided-fluvial, alluvial-fan and near-shore siliciclastics interbedded with shallow-marine carbonates. Folding, faulting and erosion took place before the deposition of a glacigene sequence in the Late Carboniferous and Early Permian (Sakmarian). After erosion in eastern areas in the early Artinskian, the glacigene sequence was followed by a major fluviodeltaic progradational phase, which graded into siliciclastic, marine-shelf deposition.

A major reorientation of depositional basins took place in the Late Permian. Depositional loci shifted to the northern Carnarvon Basin where continental and marine siliciclastics with minor carbonates were deposited in the Late Permian, Triassic and Jurassic. Onshore areas were mostly emergent and subject to erosion, and remained so throughout the Mesozoic and Cainozoic except during the transgressions in the Cretaceous and early Tertiary. During the tectonism resulting from Gondwana breakup in the Jurassic, thick clastic sequences accumulated on the downthrown side of active faults in the northern Carnarvon Basin.

By the Late Neocomian (Early Cretaceous), tectonic activity had largely ceased and planation of most of the onshore Carnarvon Basin had occurred. Sea levels rose in a major transgression, and a post-breakup transgressive siliciclastic sequence was deposited, mostly in open marine-shelf conditions. Pelagic marine-shelf sedimentation became dominant, and in the Late Cretaceous changed from siliceous to calcareous pelagic deposition.

Calcareous shelf deposition continued through the Cainozoic in the present-day coastal and offshore areas. There was minor mixed-continental and coastal, siliciclastic deposition in the Eocene and Miocene, largely in onshore areas, and lateritization and silcretization occurred in the Oligocene and Miocene.

The Late Tertiary–Early Quaternary saw the onset of arid conditions in the Carnarvon Basin, with the formation of duricrust calcrete followed by alluvial and eolian deposition and reworking in onshore areas, and continued calcareous deposition offshore.

NOMENCLATURE AND SYMBOLS

The stratigraphy of the Carnarvon Basin was first systematically compiled by Condon (1954), in a progress report on the BMR study of the Carnarvon Basin. This was revised and expanded in the light of further work by Condon (1965b, 1967, 1968). At that time, knowledge and information concerning the offshore portion of the basin was becoming available, but integration of these data had scarcely begun. Apart from the necessarily brief descriptions given by Playford and others (1975) and Thomas and Smith (1976), this bulletin is the first attempt to synthesize the mass of data into a unified whole and to develop a regional, detailed stratigraphy.

In onshore areas, the stratigraphic framework set out by Condon has been refined but not fundamentally altered, and the current stratigraphy is summarized in Figure 3. This bulletin concentrates on the sedimentology of the rock units, as this is the field in which most advances have been made since previous publications. Hocking (1985) summarized the stratigraphic changes which have been made for this bulletin.

In erecting formal stratigraphic nomenclature for the Carnarvon Basin, the term 'greywacke' was commonly used in Palaeozoic formation names by Condon (1954, 1962a) and Konecki, Condon, Dickins and Quinlan (in McWhae and others, 1958). By using the terms 'sandstone' and 'greywacke' in formation names, Condon differentiated between sand-sized siliclastic sediments with negligible matrix (termed sandstones), which are potential aquifers and hydrocarbon reservoirs, and those with significant matrix (termed greywackes), which lack economic reservoir properties. The names were altered to 'Sandstone' rather than 'Greywacke' by Hocking and others (1980), to avoid genetic connotations and possible ambiguity arising from the use of the term 'greywacke'. It remains desirable, however, to discriminate between Carnarvon Basin sandstones with negligible matrix and those with a significant matrix. To this end the sandstone classification scheme of Dott (1964) is followed here, with the minor modification outlined by Hocking and others (1980).

The term laterite is subject to some ambiguity of meaning. In this bulletin, laterite refers only to ferruginous duricrust and the leached profile with which it is associated. It does not include siliceous or aluminous duricrust. The former is termed silcrete, and the latter is not known to occur in the Carnarvon Basin.

Graphic logs of measured sections in this bulletin follow a consistent scheme wherever possible, the reference for which is shown in Figure 4. The right-hand side of the column shows grain-size, although the grain-size span varies from section to section, and the column itself shows bedform. Ancillary symbols show features such as pebbles, contorted bedding and intraclasts. Where lithology is shown in the column (primarily carbonates and subsurface sections), the symbols used are those in Figure 4. All wireline logs have been converted to a metric depth scale, which varies from log to log but can be read with a metric ruler.

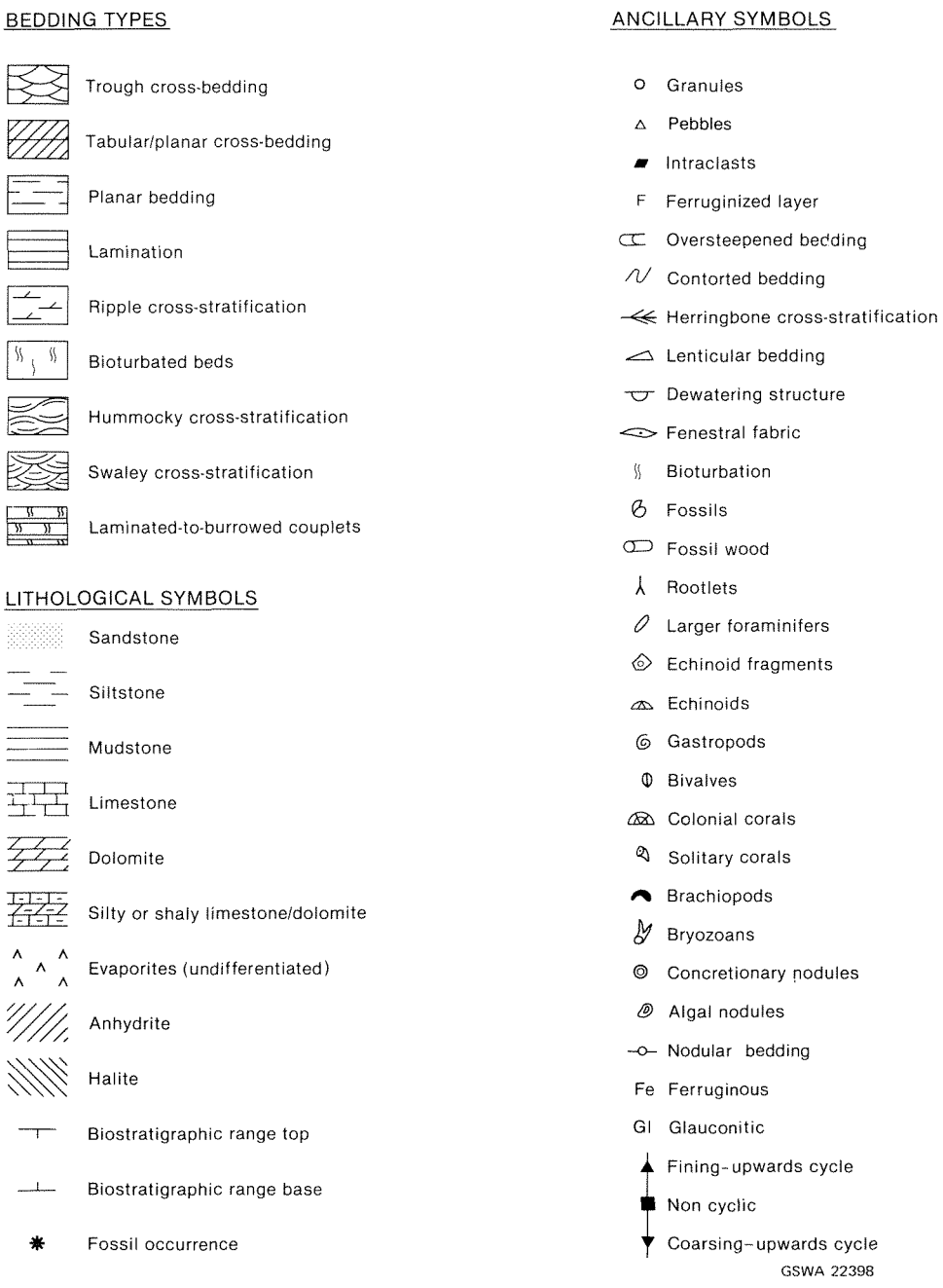


Figure 4. Legend for graphic logs of measured sections.

CHAPTER 2

Physiography

ONSHORE

INTRODUCTION

The Carnarvon Basin is mostly an area of subdued relief, although there are sizeable hills in the eastern part of the basin. It is drained by several large ephemeral rivers. From south to north these are the Murchison, Wooramel, Gascoyne, Lyons, Minilya, Lyndon, Yannarie, Ashburton, Cane, Robe, and Fortescue Rivers (Fig. 5). All of the rivers have their main catchment in areas of Precambrian or (to a lesser extent) Palaeozoic bedrock and have few if any tributaries which originate on areas of Mesozoic or Cainozoic sediments. Although the rivers only flow for a short period after heavy rain, the Wooramel, Gascoyne and Ashburton Rivers have built sizeable deltas because of the volume of sediment transported during floods. Numerous smaller creeks are present in the basin but, except for consequent creeks on the Cape Range Anticline, do not reach the sea.

The physiographic scheme presented here has developed during the Geological Survey's mapping since 1975, and is largely based on the etchplain concept, which Finkl and Churchward (1973) applied to southwestern Australia. Many of the regions correspond broadly to those of Finkl and Churchward, but local names are used. The physiographic regions outlined by Playford and others (1976) for the Perth Basin have been extended northwards, where appropriate, but the subdivision herein is generally finer than in the Perth Basin. The timing of Quaternary climatic events is based on Kukla (1977), Bowler (1976), Bowler and others (1976), and Mann and Horwitz (1979).

Three broad physiographic zones are recognized in the Carnarvon Basin (Figs 5 and 6): the coastal, transitional and inland zones. The coastal zone is dominated by constructional landforms. These consist of coastal dune belts, aggrading alluvial to deltaic plains, tidal flats and, between Carnarvon and Exmouth Gulf, anticlinal domes onlapped by Pleistocene marine and eolian sediments. The transitional zone is a generally low-relief area in which both constructional and erosional landforms are present. Alluvial plains alternate with duricrusted areas (largely calcrete), and dunefields commonly cover both. The inland zone is dominated by erosional processes. It was previously part of an extensive laterite and silcrete plateau but is now largely a semi-stripped etchplain, characterized by flat to gently undulating terrain interspersed with strike ridges, mesas and buttes. Extensive, virtually undissected duricrust, with dunefield cover, is preserved only south of the Gascoyne River (the Victoria Plateau) and in the Kennedy Range plateau.

The zones are further subdivided into regions, shown in Figure 6.

COASTAL ZONE

This is subdivided into the MacLeod, Peron, Edel and Balline Regions, and the Yanrey and Cane-Robe Tidal Flats. The Quaternary deltas of the Gascoyne and Wooramel Rivers are also part of the coastal zone but are not distinguished from the remainder of the Carnarvon Coastal Plain, which forms part of the transitional zone.

MacLeod Region

This area is characterized by a series of variably dissected anticlinal domes separated by low-lying areas infilled by Pleistocene marine and eolian sediments. The domes consist of hard Tertiary limestone and formed through post-Eocene reverse movement on pre-existing faults, which resulted in folding of the limestone. They range in size from the Cape Range Anticline, about 100 km long, 20 km wide and reaching a maximum of 315 m above sea level, to the Homestead Anticline near Minilya homestead, about 4 km long, 1 km wide and less than 20 m high. With the exception of Cape Range, the larger anticlines have a breached core, where erosion has cut through the hard limestone cap of the anticline to expose softer underlying limestones. This results in dip-slope ranges surrounding a subdued central etchplain, as

in the Giralia and Marrilla Anticlines. There is a thicker sequence of resistant limestone in Cape Range and, as a result, deep gorges have formed instead (Fig. 7). The Cape Cuvier Anticline, between Gnaraloo and Quobba, has been strongly modified by coastal erosion. This kept pace with uplift of the anticline, and the resultant cliffed coastline (see profiles in Denman and van de Graaff, 1977, Fig. 16) is almost coincident with the anticlinal axis.

Doming of the anticlines commenced in the Late Oligocene. This is indicated by the lateral change in the Mandu Calcarenite, which is a low-

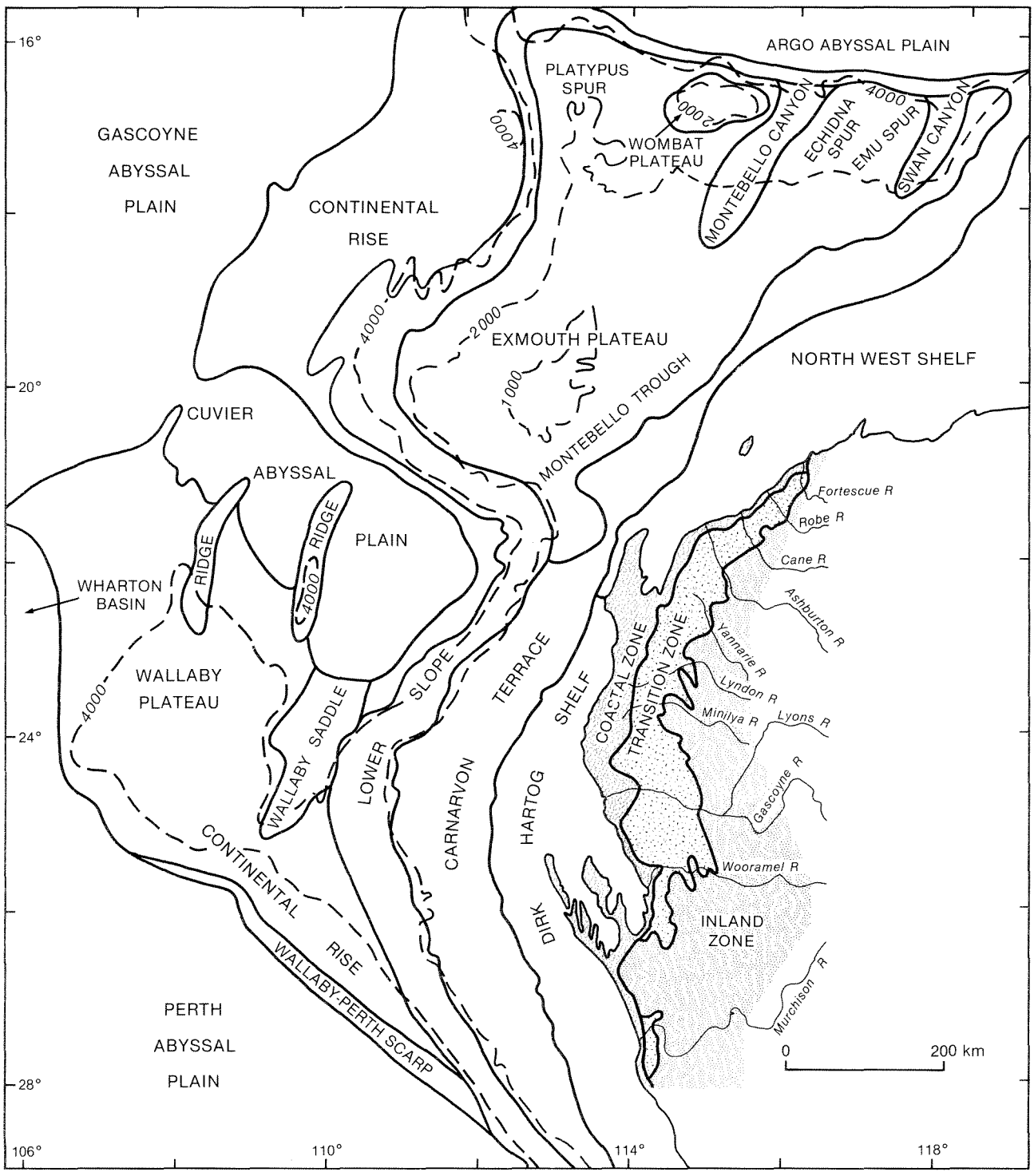


Figure 5. Broad physiographic zones, onshore and offshore Carnarvon Basin. Offshore zones and bathymetry after Falvey and Veevers (1974).

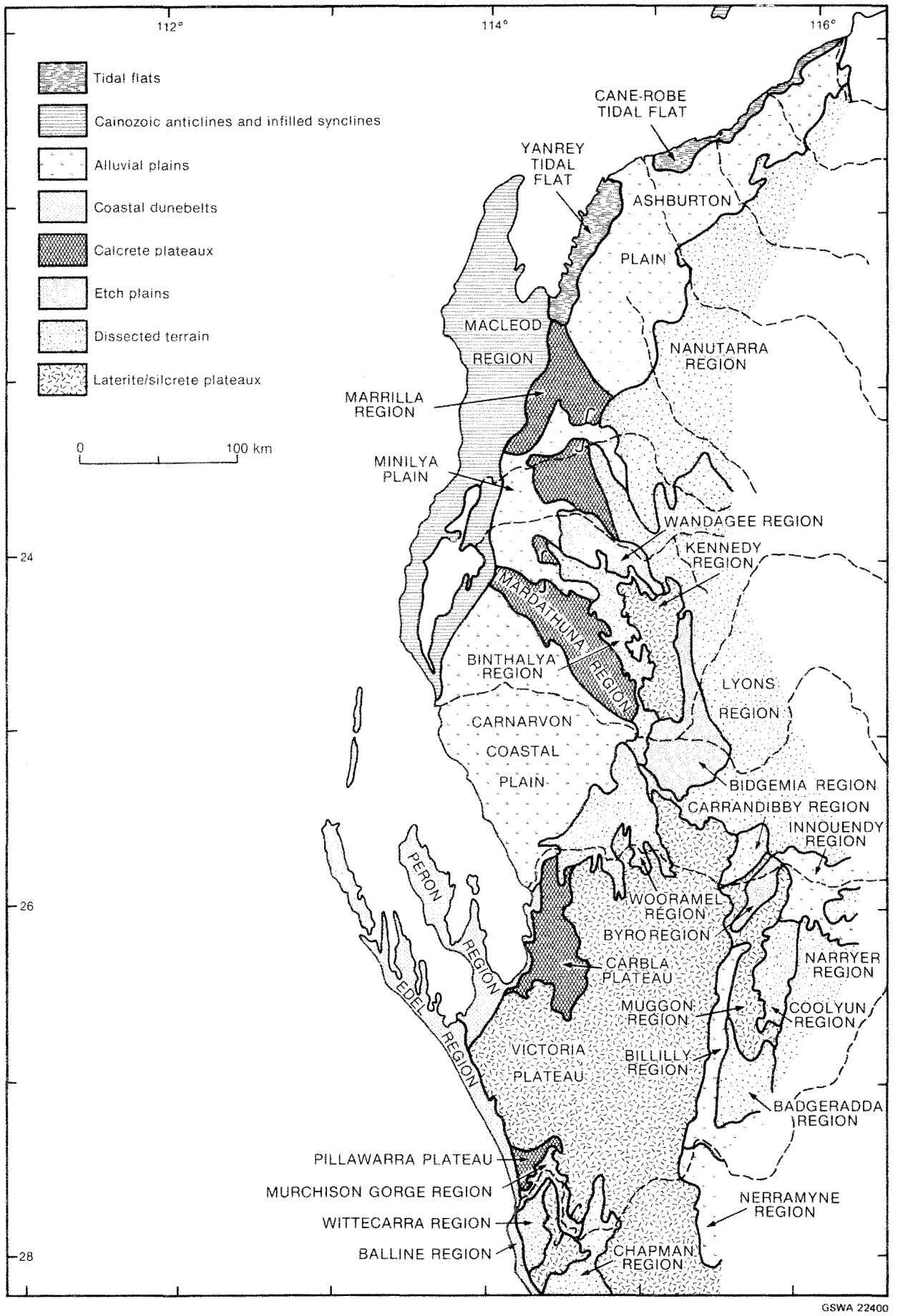


Figure 6. Physiographic regions, onshore Carnarvon Basin.

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Figure 7. **Shothole Canyon, Cape Range. *Trealla* Limestone forms hard capping over softer underlying limestone. View looks east towards Exmouth Gulf.**

energy, moderate-depth deposit in the Cape Range Anticline but contains a shallow, high-energy facies (the Bullara Limestone) in the Rough Range Anticline, and is absent in the Giralia Anticline. Emergent, tectonically warped, erosional sea-level terraces are present on the west side of Cape Range (van de Graaff and others, 1976) and around Lake MacLeod (Denman and van de Graaff, 1977). The terraces indicate that warping of the anticlines continued into the Quaternary until less than 123 000 years ago, which is the age of the youngest terrace deposit to be radiometrically dated (Veeh and others, 1979). Poorly expressed sag ponds, adjoining some anticlines east of Lake MacLeod, suggest that tectonism, and consequently warping, may still be continuing.

The low-lying area extending south between the Cape Range–Rough Range and Giralia Anticlines, from Exmouth Gulf to Lake MacLeod and ultimately to Shark Bay, was named the Bullara Sunkland by Logan, Read and Davies (1970). Exmouth Gulf was described briefly by Logan and others (1976). Except north of Exmouth, it is less than 20 m deep, and subject primarily to tidal effects; waves are dominated by local-wind effects, with oceanic swell affecting only the north and northeast parts of the gulf. Salinities appear to be oceanic. Most of the floor of the gulf is covered by argillaceous (rather than calcareous) muddy sands between 0.5 and 2 m thick, overlying pre-Holocene clay (Logan and others, 1976).

The area between Exmouth Gulf and Lake MacLeod is an extensive seif (longitudinal) dunefield in which unlithified, slightly calcareous dunes overlie an older field of calcreted, larger dunes. The unlithified dunes probably formed during the 16 000–25 000 years B.P. arid phase of Bowler and others (1976), whereas the older dunefield probably correlates with the younger (Bundera) terrace deposits on the west side of Cape Range, and is thus 120 000–130 000 years old. An older, third series of dune deposits, the Exmouth Sandstone, flanks Rough Range and the southeast side of Cape Range, but they have been extensively dissected and it is unlikely that they would have recognizable dune topography farther south.

Lake MacLeod, south of the dunefield, is a large saline playa which formed through the barring of a marine embayment: during most of the Pleistocene, Lake MacLeod was open to the sea at both ends and the presence of fossil coral reefs indicates that normal oceanic salinities prevailed (Denman and van de Graaff, 1977). The barrier at the northern end may have formed during the 16 000–25 000 year arid phase, as a result of both uplift of the small anticlines north of the

Warroora Anticline and increased dune migration, but the southern end was open until about 5 000 years B.P. At this time, the prograding Bejaling Beach Ridges blocked the southern passage and reduced Lake MacLeod to an evaporite basin. The surface of the lake is as much as 5 m below sea level and is generally dry except when the Gascoyne, Minilya or Lyndon Rivers flood. There are two areas of permanent ponds with normal oceanic salinity, on the western side of the lake, which may have a subsurface connection to the sea. The circular outline of the ponds suggests that solution of the lacustrine sediments is occurring. Between these ponds, a transverse bar divides Lake MacLeod into two basins. The bar is built on shelly limestone and probably formed as either a tombolo or a ridge at the meeting point of two flood-tide systems. Lake MacLeod has been the subject of a detailed research program by the University of Western Australia but no results have been published.

Peron Region

This area forms the northern part of the "Peron Province" of Logan, Read and Davies (1970). For convenience, it is here taken to include Lharidon Bight, Hamelin Pool, the Faure Sill and the coastal plain on the eastern side of Hamelin Pool. The shape of the peninsulas, in both the Edel and Peron Provinces, suggests that they may overlie anticlinal structures similar to those in the MacLeod Region, but this has only been proven for Dirk Hartog Island.

The Peron Region is characterized by an undulating topography of stabilized, unconsolidated, red, quartzose sand dunes. These are the "Nilemah sands" of Logan, Read and Davies (1970), and probably formed during the 16 000–25 000 years B.P. arid phase. They overlie a relic transverse dune complex (the Peron Sandstone) with dunes up to about 45 m high which formed in the Early–Middle Pleistocene. On the western side of the Peron Peninsula and Tailifer Isthmus, a strip of calcareous coastal dunes (Tamala Limestone) oversteps the Peron dunefield. Littoral deposits are present and probably correlate with the Bibra Limestone.

The history and environments of Shark Bay were described in detail by Logan, Davies and others (1970) and Logan, Read and others (1974), and summarized by Butcher and others (1984), van de Graaff and others (1983), and Logan and others (1976). Hamelin Pool and Lharidon Bight are hypersaline basins less than 10 m deep, with extensive fringing tidal flats and beach ridges. They are barred from an area of metahaline salinity to the north by the Faure Sill, a seagrass and limesand bank extending from Kopke Point to Faure Island–Petit Point and less completely to the Peron Peninsula south of Dubaut Point. Algal mats dominate the tidal flats and shallow subtidal areas, and stromatolites extend around Hamelin Pool in the tidal–shallow subtidal zone (Fig. 8). These were described by Playford and Cockbain (1976) and Playford (1980). Several factors control the distribution and morphology of the

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Figure 8. Stromatolites exposed at low tide near Petit Point on west side of Hamelin Pool. Scale (circled) is 13 cm long.

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Figure 9. Consolidated Hamelin Coquina on west side of Hamelin Pool, forming wide beach ridges. Bedding accentuated by wind action.

stromatolites, the most notable being prevailing-wind direction, wave translation direction and the presence of a hard substrate (Playford, 1980). Wide beach ridges and prograding spits occur behind and on the tidal flats (Fig. 9). They are composed of small specimens of the bivalve *Fragum erugatum*, which have had their growth stunted by the hypersaline conditions.

Prior to the Holocene, there were two marine depositional phases in Shark Bay, the Dampier and Bibra marine phases. These are thought to have occurred about 240 000 and 120 000–130 000 years B.P. respectively. In both phases, the maximum sea level was approximately that of the pre-existing dune landscape of the Peron Sandstone. The coastal plain west of Yaringa homestead is composed of these deposits. Further details are in the Cainozoic chapter.

Edel and Balline Regions

The Edel Region ("Edel Province" of Logan, Read and Davies, 1970) and the Balline Region are areas of considerable calcareous coastal-dune buildup. In the Edel Region, the dunes reach a height of 300 m (at Womerangee Hill) and are mostly lithified, whereas a sizeable area of unconsolidated, largely mobile dunes is present in the Balline Region. These unconsolidated dunes could be considered part of the Quindalup Dune System (Safety Bay Sand) of the Perth Basin.

The dunes have a north-south alignment, reflected in the orientation of Bellefin and Heirisson Prongs, Carrarang and Burabooggatta Peninsulas, and Dorre and Bernier Islands, indicating that Pleistocene wind directions were similar to present-day prevailing winds. The development of the dunes largely pre-dates the Dampier marine phase, although interfingering relationships with both the Dampier and Bibra Limestones in some areas (*e.g.* near Top Burabooggatta Well) show that dune building continued during the Late Pleistocene. Active dunefields cover most of Bellefin Prong and much of the Balline Region at present.

The Zuytdorp Cliffs (Fig. 10) form the Western boundary of the Edel Region on the mainland, and similar cliffs extend along the western side of Dirk Hartog Island. The straight line of the Zuytdorp Cliffs may be fault controlled, but no conclusive evidence is available. It is worth noting that most of the western coastline of Western Australia has this orientation, in an *en echelon* manner. The same north-northwesterly trend is a major structural trend in the Yilgarn Block, and if the Meckering Line (see Gordon and Lewis, 1980) is extended north, it approximately coincides with the Zuytdorp Cliffs. However, there is no displacement of Silurian sediments near Kalbarri, so the fault (if present) is at least 5 to 10 km offshore, at which distance there is no fault apparent on seismic data.

GSWA 22404

Figure 10. Zuytdorp Cliffs near Womerangee Hill. Cliffs are approximately 270 m high at this point.

Yanrey and Cane-Robe Tidal Flats

These are major tidal-flat, supratidal-flat and mangrove-swamp complexes. They are separated by the Ashburton River delta and beach ridges associated with it. Beach ridges also occur at the mouth of the Cane River. The Yanrey Tidal Flat was briefly discussed by Logan and others (1976).

The mangrove thickets and the adjacent landward belt of algal mats are affected by normal tides, but beyond that there is a bare, very low-gradient supratidal flat which is up to about 15 km wide and is mostly salt encrusted. Landward of this, a beach-ridge belt is present in many places. The beach ridges probably formed during cyclones, when the effective shoreline was landward of the supratidal flat because of banked-up water.

The Yanrey Tidal Flat oversteps earlier longitudinal dune and sandplain terrain, which has resulted in the formation of 'islands' of dunes standing above the otherwise featureless supratidal flats. This relationship demonstrates that the sandplain with its ubiquitous longitudinal dunes predates the Holocene transgression to which the level of the tidal flats is related.

Gascoyne River deltas

The Gascoyne River has built three deltas during the Quaternary: the Brown, Boodalia and present-day deltas (Johnson, 1974, 1982).

The present-day Gascoyne delta is a wave-dominated, arid-zone delta and was described in detail by Johnson (1982). Northwards longshore drift, under the influence of waves, has produced a major beach-ridge complex, the Bejaling beach ridges, which barred the southern end of Lake MacLeod about 5000 years B.P. During flooding of the Gascoyne River numerous crevasse-splay flood channels, which spread out from the main channel in classical delta-fan shape, become active. These extend from the Brown delta in the south to Cardabia Creek (QUOBBA) in the north, and have deposited a veneer of Holocene sediments on the Pleistocene Brown and Boodalia deltas.

The Boodalia delta is a well-preserved, presently inactive, high destructive delta with a fringe of mangrove swamps backed by saline supratidal flats. The Brown delta is largely obscured by the younger Boodalia delta, and has also been affected by extensive coastal erosion. The Brown Range is probably an old beach-ridge complex associated with the Brown delta. The Brown and Boodalia deltas probably formed at the interglacial high sea-level stands 240 000 years B.P. and 120 000–130 000 years B.P. respectively, and they show that the Gascoyne River has migrated gradually north in the Quaternary. This may be because channels to the south were continually blocked by barriers formed by northerly winds and waves, forcing the Gascoyne River north.

TRANSITIONAL ZONE

The transitional zone is subdivided into the Carbla Plateau, the Wooramel, Mardathuna and Marrilla Regions, the Carnarvon Coastal Plain and the Minilya and Ashburton Plains. The Pillawarra Plateau and the Wittecarra Region are isolated parts of the zone.

Carbla and Pillawarra Plateaus

These areas are characterized by a well-developed calcrete duricrust with which a superimposed trellis-type palaeodrainage pattern. The duricrust approximately reflects the extent of the Cretaceous Toolonga Calcilutite and presumably extends between the two plateaus, although it is covered by the late Pleistocene sandplain deposits of the Victoria Plateau.

Palaeodrainages on the eastern side of the Pillawarra Plateau are truncated by the active drainages of the Murchison Gorge Region, while those on the western side (as at Lake Coolcurdoo) are blocked by the coastal dunes of the Edel Region. On the Carbla Plateau, the lower reaches of palaeodrainages are blocked by Pleistocene and Holocene beach ridges, and the northern part of the plateau is being actively destroyed by scarp retreat of breakaways, which originated as coastal cliffs when the present-day coastal plain west of Yaringa homestead was submerged in the Pleistocene.

The age of the plateaus is moderately well defined. The calcrete post-dates both the Middle Miocene Trealla Limestone and Lamont Sandstone, and the development of laterite and silcrete: laterite and silcrete fragments are locally common in the calcrete. It pre-dates major incision of the Murchison Gorge and the dune belts of the Edel and Peron Regions. This fixes its age as latest Miocene to Pliocene, possibly extending into the Early Pleistocene. The development of the calcrete duricrust is considered to have taken place under relatively arid conditions, unlike laterite and silcrete development, which occurred in a more humid, possibly strongly seasonal, climate.

Mardathuna and Marrilla Regions

These are also calcrete duricrusted areas, but the calcrete is mostly obscured by dunefields which in large part formed during the 16 000–25 000 year B.P. arid phase of the Pleistocene. The duricrust has been breached by major rivers, resulting in areas of duricrust separated by alluvial plain. Low scarps, such as are present near Winning homestead and along the line of Chinkia Creek, commonly bound the duricrust, and small etchplains are locally developed at the base of the scarps (*e.g.* between Karrajong Dam and Merrebello Pool, WINNING POOL). The duricrust is developed primarily on the Cretaceous Windalia Radiolarite and Toolonga Calcilutite, and probably formed in the latest Miocene–Pliocene, as in the Carbla and Pillawarra Plateaus.

Wooramel Region

This area is transitional between the Victoria Plateau and the Carbla Plateau and Carnarvon Coastal Plain. The southern part of the region is dominated by a broad palaeodrainage valley associated with the Wooramel River and its ancestral tributaries, while the northern part is a longitudinal dunefield underlain by laterite and silcrete with some calcrete near the margins.

Wittecarra Region

This is a moderately dissected area with a discontinuously preserved lateritic duricrust which slopes down from the Victoria Plateau to the coast at Kalbarri. Some calcrete-capped remnants of the Pillawarra Plateau (notably Meanarra Hill) stand above the general level of the region. They indicate that the laterite slope, which characterizes the Wittecarra Region, formed after the breaching of the Pillawarra Plateau by the Murchison River. Palaeodrainages in the Wittecarra Region are blocked or diverted by the coastal dune belt of the Balline Region south of Kalbarri near Balline, and laterite is present almost at river level near Murchison House homestead. This suggests the Wittecarra Region formed at about the same time as the main incision of the Murchison River gorge, in a more humid climate than prevailed during the formation of calcrete duricrust. This was probably in the Late Pliocene–Early Pleistocene, based on the inferred ages of calcretization and coastal-dune buildup.

Carnarvon, Minilya and Ashburton Plains

The Minilya Plain and Carnarvon Coastal Plain both formed initially by the breaching of the calcrete duricrust of the Carbla Plateau and Marrilla and Mardathuna Regions. Subsequent scarp retreat led to the formation of broad alluvial plains. It is doubtful whether there was any widespread duricrust initially in the area of the present-day Ashburton Plain.

Widespread alluvial deposition, brought about largely by lateral migration of river channels, produced plentiful unconsolidated sand, and this was reworked during the last glacial arid period (16 000–25 000 years B.P.) into large fields of longitudinal dunes. In some areas, these have in turn been reworked into a distinctive dune and playa terrain. This terrain is best developed near rivers (particularly the Wooramel, Gascoyne and Ashburton Rivers) and may be due to more frequent flooding and, locally, higher water tables.

The formation of a broad alluvial plain by the lateral migration of river courses is clearly illustrated by the Gascoyne River. The northwards migration of the river from the Brown Delta to the present-day delta is discussed above: prior to this, palaeodrainages originating near Mooka can be traced south to the present-day Wooramel River delta and north to Cooralya. These form a delta-shaped alluvial plain with an area of about 10 500 km^2. The drainages post-date the Carbla Plateau but pre-date the Brown Delta, and any deltas developed by them were destroyed prior to the Bibra high sea-level stand, which suggests that they were active in the Late Pliocene. Longshore drift and eolian reworking of them may have provided a source for much of the Exmouth Sandstone.

INLAND ZONE

The inland zone contains a wide range of landforms from well-preserved duricrust plateaus, through variably dissected duricrust terrain, to etch plains and palaeodrainage valleys. It is subdivided into 18 physiographic regions.

Victoria Plateau, Kennedy Region and Muggon Region

These were originally part of a single duricrust plateau. The Victoria Plateau is a gently undulating sandplain, with minor dunefields, underlain by laterite and silcrete. Indistinct palaeodrainage patterns are present on the plateau but because of the relatively thick cover of unconsolidated sand, most of which has undergone some eolian reworking, no completely integrated palaeodrainage system can be reconstructed. The duricrust is developed on the ?Miocene Pindilya Formation or, near Shark Bay, the Lamont Sandstone, which suggests the plateau developed largely in the Late Miocene–Early Pliocene. The dunes probably formed in the 16 000–25 000 years B.P. arid phase.

The Kennedy Region consists of the sand covered, duricrusted Kennedy Range plateau and the immediately adjoining area of rugged topography. Because of the protective sandplain and duricrust, dissection of the plateau is restricted to headward erosion by numerous creeks. The main phase of laterite and silcrete development probably occurred in the Oligocene. The Eocene Merlinleigh Sandstone (which caps the range) is lateritized, and duricrusted surfaces (on the west of the range) are displaced over faults which are thought to have moved in the Middle–Late Miocene. Duricrust development probably continued into the Miocene, but it is not readily distinguished. Two generations of dunes are present on Kennedy Range. Dissected, consolidated dunes can be recognized northeast of Venny Peak and near the ruins of Merlinleigh homestead, and probably correlate with the Peron Sandstone (Late Pliocene—Early Pleistocene). The main stabilized, but unconsolidated, dune field probably formed in the 16 000–25 000 years B.P. arid phase. Dunes do not ascend the flanks of Kennedy Range anywhere, indicating that the sand is locally derived.

The Muggon Region is an eastwards extension of the Victoria Plateau which has suffered only minor dissection since its formation in the Miocene. The duricrust is mostly silcrete, reflecting the kaolinitic nature of the underlying rocks.

Lyons, Carrandibby, Nanutarra, Binthalya, Coolyun, Chapman and Narryer Regions

These are semi-stripped etchplains with varying amounts of preserved duricrust. The Lyons Region is characterized by gently undulating terrain, parts of which are etchplains, interspersed with strike ridges of resistant limestone and sandstone. Isolated duricrust remnants are present, of which Moogooloo Hill is most prominent. In some areas underlain by Precambrian bedrock, intensely dissected terrain has developed with a dense, dendritic drainage pattern. The Carrandibby Region is a large isolated area of this terrain.

In the Nanutarra Region, dissection of the duricrusted, flat-lying Mesozoic sediments has led to a terrain of scattered mesas and buttes interspersed with flat alluvial plains and dunefields (Fig. 11). Exhumation of the Early Cretaceous landscape (see the section on the Nanutarra Formation also Hocking and van de Graaff, 1978) has resulted in local rugged ranges,

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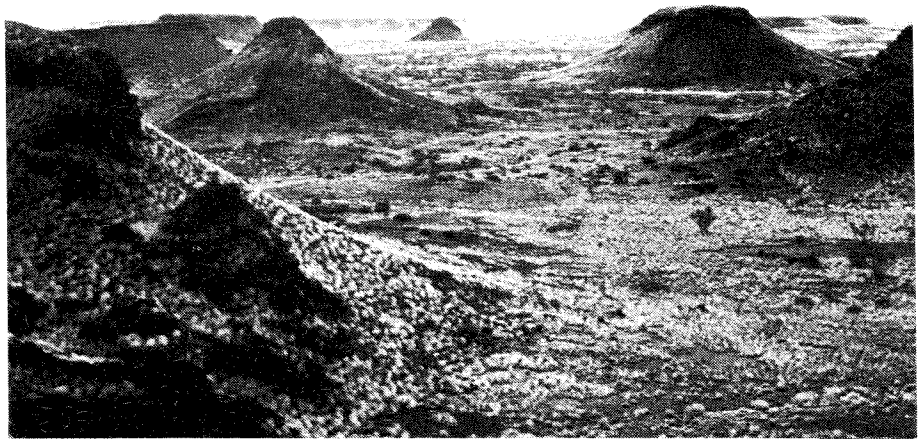

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Figure 11. Mesas and buttes of Cretaceous Nanutarra Formation overlying exhumed terrain of Precambrian rocks, Jubricoo Creek area.

strike ridges (*e.g.* Parry Range) and domed inselbergs (*e.g.* Jundelaya Hill) of Precambrian rocks.

The Binthalya Region is a generally gently undulating area, with dense dendritic drainage and minor silcrete remnants, underlain by Windalia Radiolarite. The eastern part of the region grades into the duricrust plateau of the Kennedy Region by way of topographically stepped (because of faulting) duricrust surfaces and a general increase in elevation.

The Coolyun Region is characterized by claypan and dune terrain which resulted from the extensive destruction of a silcrete duricrust by a north-flowing palaeodrainage. Scattered silcrete remnants form low rises, mostly around the margins of the region. A well-developed, partly sand covered, etchplain is developed on the Byro Group between Coolyun Hill and Mulyajingle Peak.

The Narryer Region lies to the east of the Coolyun Region and is underlain solely by Precambrian rocks. It consists of gently undulating hills of Precambrian with scattered, low, duricrust remnants separated by wide alluvial depressions. It is thus similar, except in drainage density, to the Binthalya Region. Isolated inselbergs rise above the general topographic level. The most prominent of these are Mount Rebecca and Earilier Hill, which are isolated remnants of the Badgeradda Region.

The Chapman Region is a moderately dissected area breaching the victoria Plateau and corresponds closely to the outline of the Northampton Block. It contains residual clayey and sandy soils derived from the Northampton Block and scattered remnants of the Victoria Plateau.

The duricrust in these regions formed in the Oligocene or, south of the Gascoyne River (approximately), the Miocene. Most of the shaping of the landscape occurred in the Late Pliocene–Pleistocene.

Byro, Bidgemia and Wandagee Regions

These regions are well-developed etchplains which have developed primarily on fine-grained sediments of the Permian Byro Group (Fig. 12). Duricrust remnants are rare. At the end of duricrust formation, these regions were probably already the sites of the ancestral Murchison–upper Wooramel (see below), Gascoyne and Minilya Rivers. The subsequent downcutting and lateral shifting of these river courses developed the etchplains in the Pliocene and Pleistocene. Extensive alluvial fans and dunes in the Bidgemia and Wandagee Regions developed primarily in the Late Pleistocene.

Billilly, Nerramyne and Innouendy Regions

These are major palaeodrainage depressions which have been controlled largely by the juxtaposition of soft Phanerozoic sediments and hard Precambrian rocks. The Billilly and Nerramyne Regions are characterized by large saline playas and breach the Victoria Plateau, but silcrete also dips beneath the valley-fill deposits, implying that a drainage depression existed when the plateau formed in the Miocene–Pliocene. The Innouendy

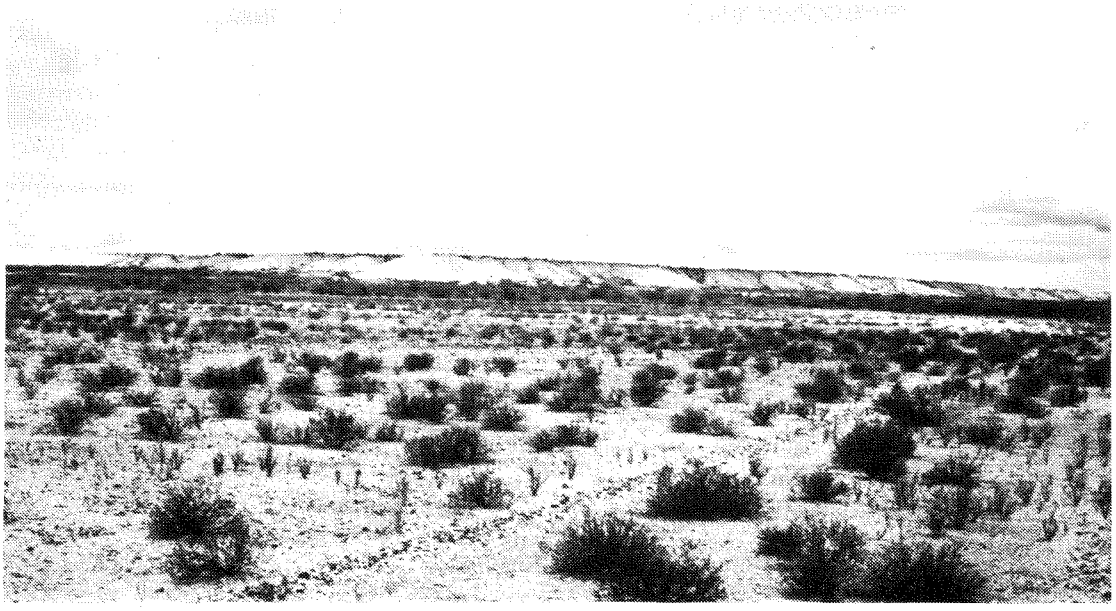

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Figure 12. Well-developed etch plain with thin alluvial cover, developed on Permian Byro Group sediments south of Wandagee Hill. Cretaceous Windalia Radiolarite forms scarp in background, which is retreating at the level of the unconformity rather than by progressive erosion.

Region is a broad featureless alluvial/colluvial plain, locally covered by dunefields and dune and playa terrain, which formed in an embayment of the Permian Lyons Group. The plain is crossed by the Wooramel River and Bilung Creek, which have cut gorges into a 30 to 40 m thick sequence of semi-consolidated alluvial deposits. The gorges open downstream into the Byro Plains, and terminate upstream at abrupt knick points (Williams, Williams and Hocking, 1983), one of which is at Bilung Pool. As in the gorge which the Wooramel River has cut further downstream, between Callytharra Spring and Deep Pool (WOORAMEL), the sediments have undergone incipient lateritization and groundwater calcretization. The laterite may be coeval with laterite in the Wittecarra Region. The Innouendy Region could have developed at virtually any time from the Late Miocene to the Pleistocene.

The Wooramel River has undergone major changes in its course in the Cainozoic, as shown in Figure 13. The headwaters of the river originally flowed down Yarra Yarra Creek and the Billilly Region into the Murchison River, as noted by Williams, Williams, and Hocking (1983). The river changed to its present course after it breached the Victoria Plateau, forming the downstream Wooramel River gorge.

Badgeradda Region

This is a rugged topographic area formed by the Proterozoic sediments of the Badgeradda Group and Nilling Formation and bounded on the west by the Woodrarrung Range. It is higher than the Victoria Plateau but has no preserved duricrust and is therefore assumed to be older. It may have formed in the early–middle Tertiary. Playford and others (1976) applied the name to a much broader area.

Murchison Gorge Region

West of the Northampton Block, the Murchison River has incised a deep gorge into the Silurian Tumblagooda Sandstone which Finkl and Churchward (1973) considered to be an etch entrenchment. Upstream of Mount Curious, the gorge is narrow and youthful, and incision has fixed the river course into a distinct meandering pattern (best shown by The Loop) with locally evident structural control (as at the Z Bend, see Frontispiece). Further downstream, the river valley becomes more mature in shape and cut-off meander cores (*e.g.* Red Hill, Tumblagooda Hill) indicate significant lateral shifting of the river course occurred during incision. Two stages of incision are apparent in the youthful part of the gorge. The later stage, marked by a steep narrow gorge, took place in the Cainozoic (?Late Miocene to Quaternary) after uplift of the area. This was associated with reverse movement on the Hardabut Fault and the formation of the Hardabut Anticline, a small anticline similar to those in the MacLeod Region. The earlier stage is marked by a more gentle slope, down from the

Victoria Plateau. This slope was present in the Miocene, as some duricrust and silicified post-Silurian sandstone (probably Miocene Lamont Sandstone, but possibly Cretaceous Birdrong Sandstone) occurs below the highest Silurian outcrops.

The Murchison River valley may even have existed in the Cretaceous, as small outcrops of possible Windalia Radiolarite occur at least 20 m below the highest Tumblagooda Sandstone near the Z Bend. This, together with the upstream extent of the Triassic Kockatea Shale along the

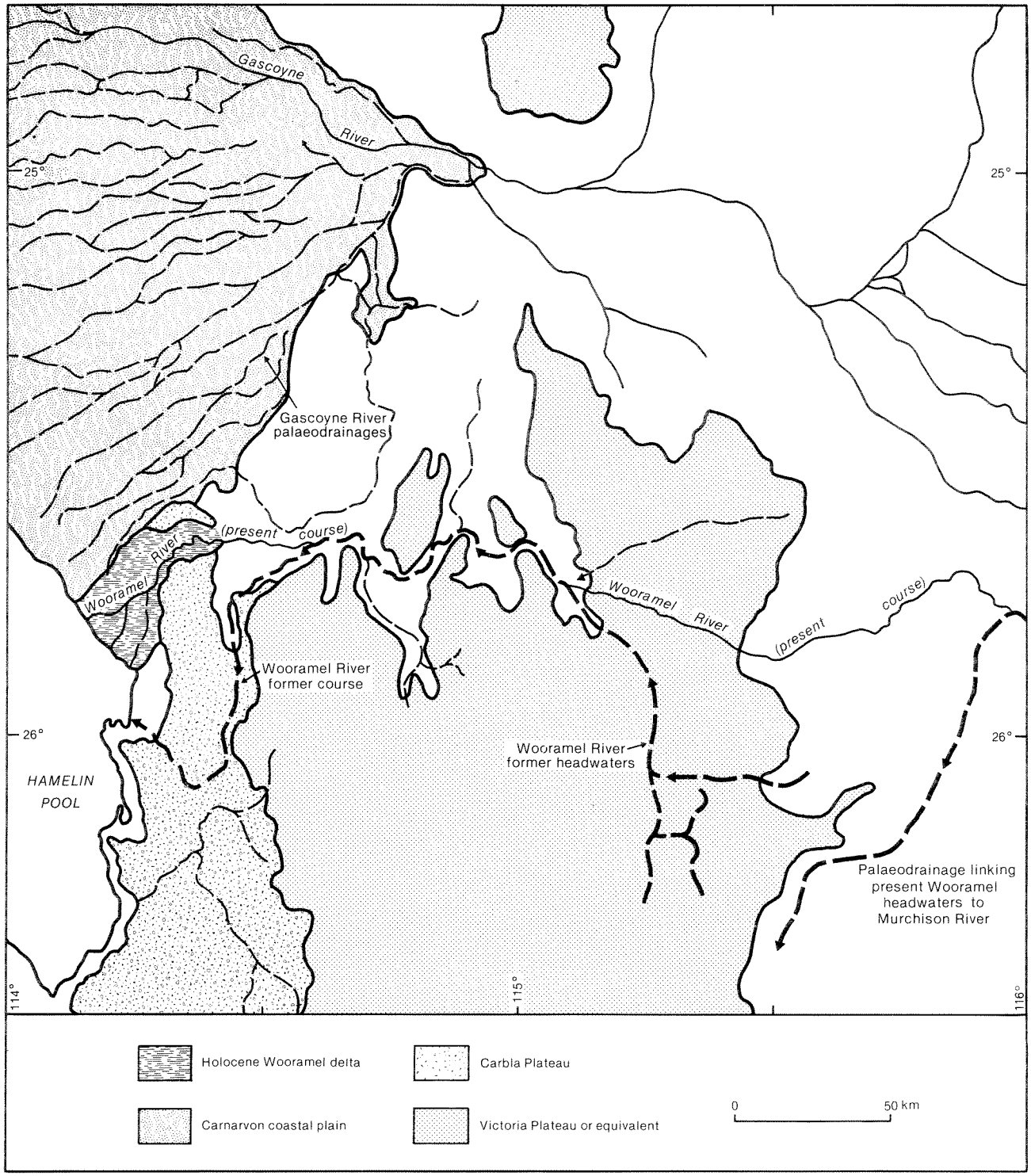

Figure 13. Wooramel and Gascoyne River palaeodrainages, illustrating changes in course of the Wooramel River since the ?Miocene. After Denman and others (1985).

Greenough River valley (but not elsewhere on GERALDTON), suggests that some of the drainages in the southern Carnarvon Basin/northern Perth Basin may have existed in approximately the same position for a remarkably long time, even surviving the breakup of the Gondwana supercontinent.

PHYSIOGRAPHIC DEVELOPMENT

The oldest element of the present-day landscape is the laterite and silcrete surface, which formed in the Oligocene in the northern Carnarvon Basin and the Miocene in the southern Carnarvon Basin. Extensive areas of this duricrust are now present only in the Kennedy Region and the Victoria Plateau. However, some drainages already existed when the duricrust developed (Billilly, Nerramyne and Murchison Gorge Regions), and in the case of the Murchison Gorge Region the drainages may date back to the Early Cretaceous. Uplift of the coastal anticlines in the MacLeod Region also commenced in the Oligocene, but they were still largely submarine features. The duricrust was breached after the Middle Miocene, but probably no later than the Early Pliocene. Drainage patterns and rates of denudation were strongly dependent on bedrock lithology.

A number of alternately arid and humid phases followed, associated with the gradual drying-out of Western Australia (van de Graaff, Crowe, and others, 1977; Wyrwoll, 1979). Only some deposits and surfaces which indicate these phases can be related to one another, and the ages are uncertain. Wyrwoll (1979) discussed possible mechanisms for the increasing aridity.

The calcrete duricrust of the transitional zone formed furing an arid phase of the Pliocene when groundwater movement was sluggish (Mann and Horwitz, 1979). Following this, more humid conditions saw the breaching of the calcrete surface and the development of major drainages. The alluvial plains of the transitional zone began to develop through scarp retreat of the duricrust surface and incision of the Murchison Gorge became pronounced. The older, consolidated alluvial sediments of the Innouendy Region were probably deposited largely during this humid phase, and the laterite surface of the Wittecarra Region began to form.

A return to arid conditions is indicated by the widespread, semi-consolidated older eolianite on Kennedy Range, in the Peron Region and, to a lesser extent, elsewhere. Bowler and Jones (1979) noted that arid conditions commenced less than 700 000 years B.P. in southeastern Australia, but the stratigraphic and geomorphological setting of these eolianites suggests that they formed somewhat earlier, possibly in the Late Pliocene–Early Pleistocene. They may correlate with the older of the two sets of dunes recognized in the Exmouth Gulf area by Wyrwoll (1979). Valley calcretes in the eastern Carnarvon Basin, which Mann and Horwitz (1979) considered began to form more than 36 500 years B.P., may have begun to develop at this time.

Repeated transgressions and regressions in the Pleistocene resulted from glacial retreats and advances and were associated with humid and arid phases. The greatest effects were in the coastal zone of the Carnarvon Basin. The marine and shoreline deposits of the MacLeod Region and the Shark Bay area formed at transgressive peaks, while the coastal dune belts of the Edel and Balline regions formed largely during regressive periods. Doming of the coastal anticlines, by now emergent, continued as did alluvial and eolian modification of the transitional and inland zones.

A wet phase between 25 000 and 40 000 years B.P. was recognized in eastern Australia by Bowler and others (1976). The alluvial plains of the transitional zone approached their present extent, and rivers had assumed approximately their present course. An intense arid period followed, from 16 000 to 25 000 years B.P. (Bowler, 1976; Bowler and others, 1976; Jennings, 1975; Wyrwoll, 1979). Major eolian reworking of surface sand occurred, forming the younger of Wyrwoll's two dune units. The resultant large longitudinal dunefields locally obscure the boundaries of physiographic regions.

The land surface of the Carnarvon Basin has since been largely static, except in the coastal zone. Here, the Faure Sill developed in the Late Pleistocene–early Holocene, barring Hamelin Pool and Lharidon Bight; the southern end of Lake MacLeod was barred by the Bejalling Beach Ridges, turning Lake MacLeod into an evaporite basin; and Exmouth Gulf and the tidal flats to the east and northeast developed. Uplift of the coastal anticlines may still be continuing and significant reworking of coastal dunes occurs in some areas.

OFFSHORE

INTRODUCTION

Two main factors have influenced the seafloor morphology of the offshore Carnarvon Basin. There is a strong tectonic control due to the rifted origin of the continental margin, and a thick wedge of Cainozoic carbonate has prograded over

shallower offshore areas to form a wide shelf. The shelf, slope and rise of most continental margins can be recognized, together with several marginal plateaus which are separated from each other by abyssal plains bounded by transform faults (Fig. 5).

SHELF

The shelf is entirely due to the presence of a Cainozoic wedge of carbonate and is typified by shallow seaward gradients, usually less than 0°05′. The 200 m isobath approximates the shelf/slope boundary. The width range from over 350 km just north of the Carnarvon Basin, to about 15 km adjacent to North West Cape. This narrowing, off North West Cape, allows the differentiation of two separate regions.

North West Shelf

The northern portion of the continental shelf was originally called the Rowley Shelf by Fairbridge (1953a), but general usage has led to the acceptance of the name North West Shelf (Exon and Willcox, 1978). It is generally 150–200 km wide. Near Onslow a large area with water depths 25 m or less protrudes onto the shelf. This is an offshore extension of the eastern margin of the onshore coastal zone, and is due to late Tertiary tectonism. Barrow Island is a large anticline of Miocene limestone whilst the Montebello Islands are recent coralline accumulations growing on a submerged extension of the Barrow Island Arch. Other islands on the shelf are either shoals or slightly higher areas of Pleistocene sediments, largely dunes. Exmouth Gulf is not recognized as being part of the shelf.

Dirk Hartog Shelf

This is somewhat narrower, with an average width of about 100 km. In the south an area of shallow water extends from the Perth Basin as the Houtman Abrolhos archipelago. The Shark Bay area is not regarded as part of the shelf.

SLOPE

The continental slope is divided into an upper slope with gradients up to 5° (but more usually in the range of 1°–2°) and a lower slope with steeper gradients, locally reaching 20°. The slope also contains canyons which begin on the upper slope and become deeply entrenched in the lower slope.

North of North West Cape, the upper slope is extended westward 350 km by the presence of the Exmouth Plateau. South of the Cape, the Carnarvon Terrace has a narrower slope.

Carnarvon Terrace

This extends arcuately for approximately 800 km and is centred offshore from Carnarvon. The maximum width of 115 km occurs at the middle, and it slowly tapers towards either end. It commences at a water depth of approximately 400 m and dips at angles between 0.5° and 1° to a depth of 1600 m. It was originally defined by Branson (1974), using a combination of bathymetry and underlying structure. Veevers and Cotterill (1978) tended to amalgamate it with the Dirk Hartog Shelf, but this appears unjustified.

Exmouth Plateau and adjoining areas

The Exmouth Plateau was restricted by Falvey and Veevers (1974) to south of latitude 16°30′S. It extends southwards some 750 km to North West Cape and has a width of 300 to 500 km. Major tectonic fracture systems form the northern and western margins, resulting in a rectilinear to slightly trapezoidal outline. The southern boundary is formed by the simple linear transform of the Cape Range Fault Zone. The northern boundary is more complex, with a tectonically dependent graben separating an outer trend, part of which has been called the Wombat Plateau (Branson, 1974; Willcox and Exon, 1976). A number of deep troughs or canyons also occur in this northern area.

The eastern boundary is formed by the Montebello Trough, a synclinal region which may owe its origin to the same processes that formed the Exmouth Plateau Arch, or may be due to flexure in the continental slope due to the loading effect of the thick Cainozoic wedge, as suggested by Falvey and Veevers (1974). It plunges northwards ending in a canyon on the lower slope, but also extends the whole length of the plateau and increases in magnitude to the south, where it again passes into a group of canyons on the lower slope. Falvey and Veevers recognized a knick point on the plateau and separated a smaller plateau proper from an edge zone, but this is probably an artifact of contiguity with the Montebello Trough, and not a true boundary.

Falvey and Veevers suggested that the Exmouth Plateau was a foundered piece of the continent, but the present elevation of (for example) the Triassic on the Exmouth Plateau is actually very close to that on the Rankin Platform.

The lower slope runs adjacent to the upper around the Exmouth Plateau and Carnarvon Terrace. It is rarely over 50 km wide and less than 20 km along the northern edge of the Exmouth Plateau. It is dissected in numerous places by canyons.

Wallaby Plateau

This is similar morphologically to the Exmouth Plateau, but different geologically. It too is bounded by transform faults to the north (Cuvier Fault Zone) and south (Perth-Wallaby Fracture Zone), and is separated from the continent shelf by a trough (the Wallaby Saddle) plunging gently to the north. However, it is smaller than the Exmouth Plateau (approximately 25 km on each side) at a greater water depth (2500 m as opposed to 900 m), and is asymmetric in slope (sloping markedly southwards) rather than antiformal.

CONTINENTAL RISE

This is an apron of sediment between the continental slope and the abyssal plains, and has an intermediate gradient. The relief is usually low due to the burial of relic topography by sediments, but areas of only partly buried hills occur on the northwestern and southwestern corners of the Exmouth Plateau. The rise is mostly a narrow zone but widens in places, for example west of the Exmouth Plateau and southeast of the Wallaby Plateau.

ABYSSAL PLAINS

Abyssal plains surround the continental margin. They have been divided into the Argo Abyssal Plain to the north, the Gascoyne and Cuvier Abyssal Plains and the Wharton Basin to the west, and the Perth Abyssal Plain to the south. Their origin by seafloor spreading is confirmed by the relationship of bottom features (*i.e.* ridges in Cuvier Abyssal Plain) to magnetic anomalies crossing the plains. They are generally deeper than 5000 m.

CHAPTER 3

Silurian

Silurian sediments are exposed in the southern Carnarvon Basin and northern Perth Basin, and are known to form subcrops in most of the Gascoyne Sub-basin and the western part of the Merlinleigh Sub-basin. The sequence consists of two thick couplets, of quartzose "red-bed" sandstone and shallow-marine dolomite with significant amounts of evaporite minerals. The units of the lower couplet have previously been named as the Tumblagooda Sandstone and Dirk Hartog Formation. The names Kopke Sandstone and Sweeney Mia Formation were proposed by Hocking (1985), for the upper couplet which was previously included in the Dirk Hartog Formation; and the name Kalbarri Group was proposed for the Silurian sequence as a whole. Only the Tumbalgooda Sandstone is exposed.

The age of the sequence was established in 1957, when the Dirk Hartog Formation was discovered in Dirk Hartog 17B and dated (Glenister and Glenister, 1957). The ages of the other three units are still doubtful, as they are based primarily on the established age of the Dirk Hartog Formation. The Sweeney Mia Formation may extend into lowermost Devonian.

KALBARRI GROUP

The Kalbarri Group (Hocking, 1985) consists of (in ascending, apparently conformable, order) the Tumblagooda Sandstone, Dirk Hartog Formation, Kopke Sandstone and Sweeney Mia Formation. It is named after the town of Kalbarri, at the mouth of the Murchison River, and encompasses all the known Silurian sediments of the Perth and Carnarvon Basins. Figure 14 shows the lithofacies relationships of the Kalbarri Group in the Shark Bay–Kalbarri area. In this bulletin, the sediments between 354 and 2749 m (total depth) in Edel 1 are assigned to the Tumblagooda Sandstone. This is a tentative correlation, and is discussed further in "Igneous and sedimentary rocks in Edel 1", at the end of Chapter 7.

The Kalbarri Group was proposed because the two siliciclastic units, the Tumblagooda Sandstone and the Kopke Sandstone, have virtually identical lithologies and inferred depositional environments, as do the two carbonate units, the Dirk Hartog Formation and the Sweeney Mia Formation. The depositional environments of the carbonate and siliciclastic units can be related to a single broad depositional setting. The sediments thus form a single phase of sedimentation which warrants recognition as a group.

TUMBLAGOODA SANDSTONE

Definition

The Tumblagooda Sandstone was named by Clarke and Teichert (1948) and formally defined by Konecki and others (1958) although Johnstone and Playford (1955), in an unpublished report, described the unit in some detail and designated its type section. It is a red-bed sequence consisting of fine- to coarse-grained sandstone with some granule to pebble conglomerate, very minor siltstone and claystone and, in the subsurface, disseminated evaporites.

The type section of the Tumblagooda Sandstone extends for approximately 70 km along the lower Murchison River, between the Hardabut Fault and Second Gully (Fig. 15), and was described by Hocking (1981). It consists of numerous partial sections (because of low dips), and has a faulted base and eroded top. The base of the Tumblagooda Sandstone has not been penetrated in any well. Forty kilometres north of the type section, in Kalbarri 1, the Tumblagooda Sandstone is conformable beneath the Upper Silurian Dirk Hartog Formation. Hocking (1981) concluded that the type section should be regarded as an indicator of trends in sedimentation rather than a single stratigraphic section. This conclusion is reinforced by the discovery of another fault of unknown magnitude at Lockwood Springs

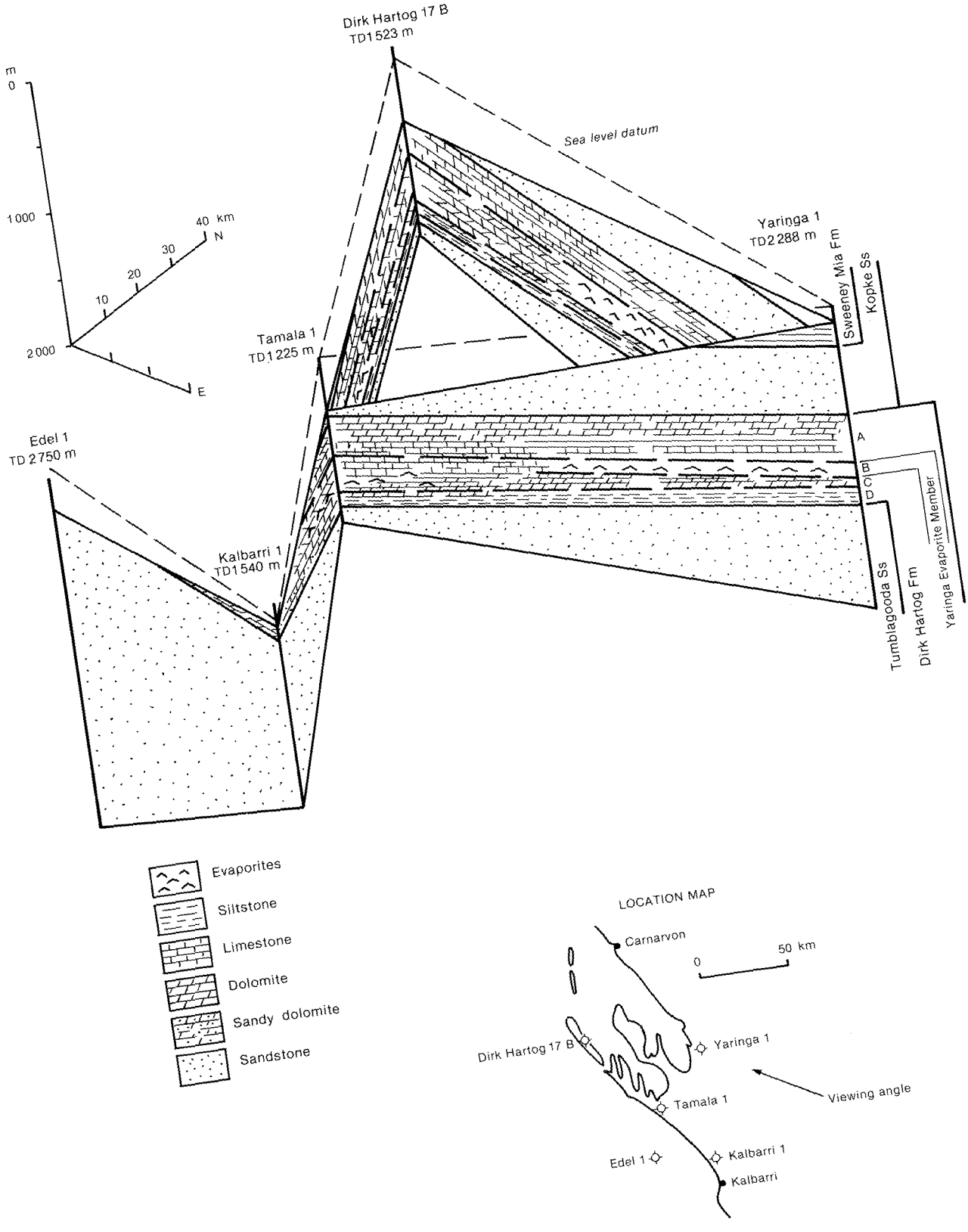

Figure 14. Fence diagram of Kalbarri Group between Shark Bay and Kalbarri, showing broad lithofacies relationships an subdivisions.

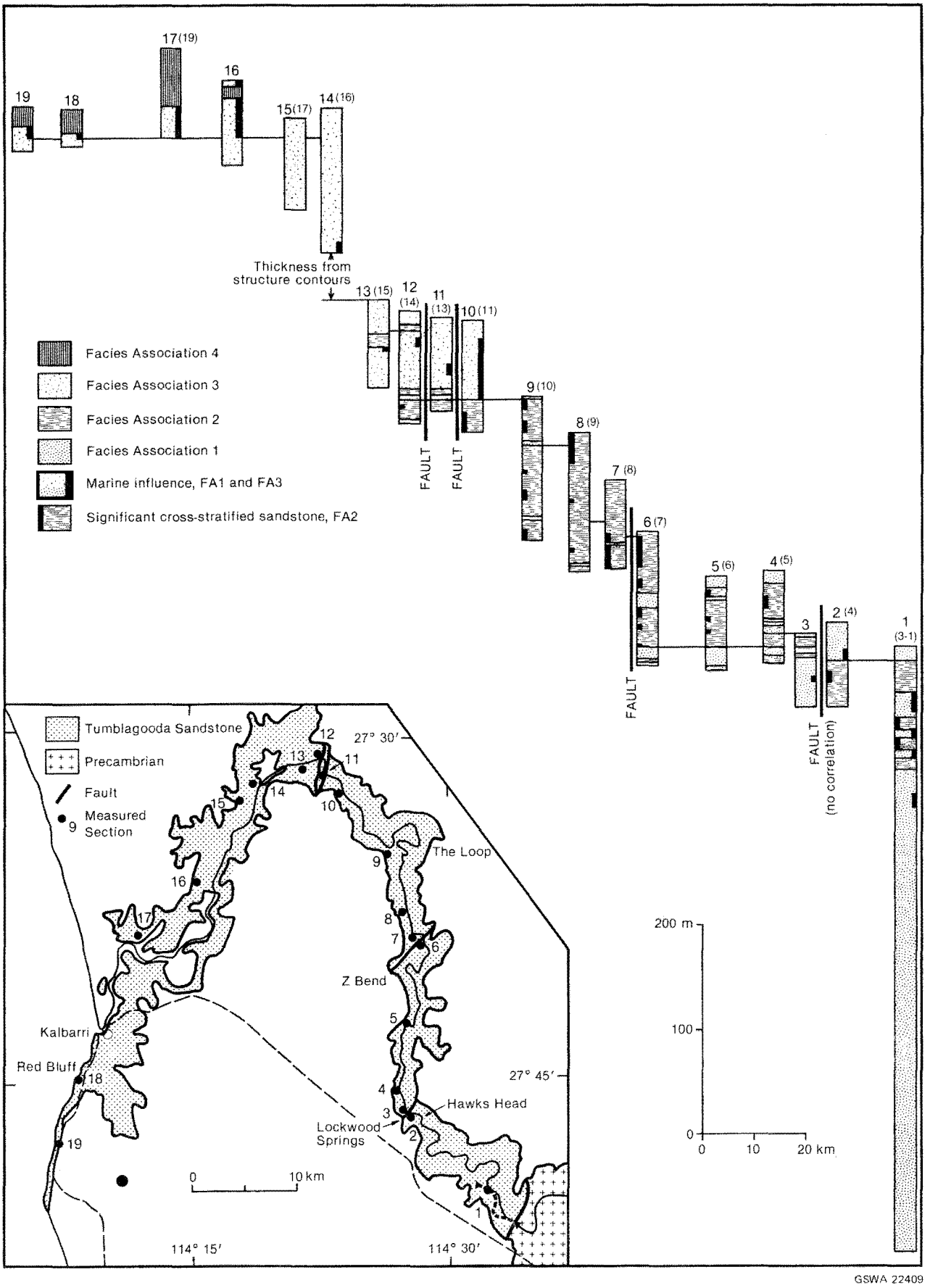

Figure 15. Type section of Tumblagooda Sandstone, simplified from Figures 2 and 3 of Hocking (1981).

(between Sections 2 and 3 of Fig. 15) which makes it impossible to give a single figure as the stratigraphic thickness of the Tumblagooda Sandstone in the type section.

Lithology

The Tumblagooda Sandstone is almost entirely sandstone, ranging from very fine-grained to very coarse-grained and pebbly. Only very minor siltstone and mudstone are present. In subsurface intersections, disseminated anhydrite is common. The sandstone is a classical "red-bed" sequence, with intense hematite-goethite staining throughout the sequence. This formed during or very shortly after deposition, as the colouration clearly outlines sedimentary structures and persists at depth in the subsurface. In thin section, dust rims occur on most grains and clearly pre-date optically continuous quartz overgrowths. Several facies are present, and these can be grouped into five facies associations (Fig. 16), four of which occur in subsurface cores and in or near the type section. The associations are statigraphically distinct as well as sedimentologically distinct.

Facies Association 1 (FA 1): This consists predominantly of trough cross-stratified, fine- to very coarse-grained, poorly to moderately sorted sandstone, with minor granule and pebble conglomerate. The thickness of the troughs varies between 10 cm and more than 1 m, with 40 to 60 cm being the most common thickness. Minor horizontal stratification and planar cross-bedding are present. Oversteepened or contorted foresets are common, as are fining- and thinning-upwards cycles, 2 to 10 m thick. Palaeocurrents are unimodal, in a westerly to northerly direction, and show a low scatter at any one locality or horizon. Trough cosets are laterally persistent, with little indication of pronounced channelling (Fig. 17).

Facies Association 2 (FA 2): The second association can be divided into 5 relatively distinct facies, some of which are shown in Figure 18. These are horizontally-stratified sandstone, medium- to large-scale cross-bedded sandstone, small- to medium-scale cross-bedded sandstone, bioturbated sandstone, and thin sand sheets.

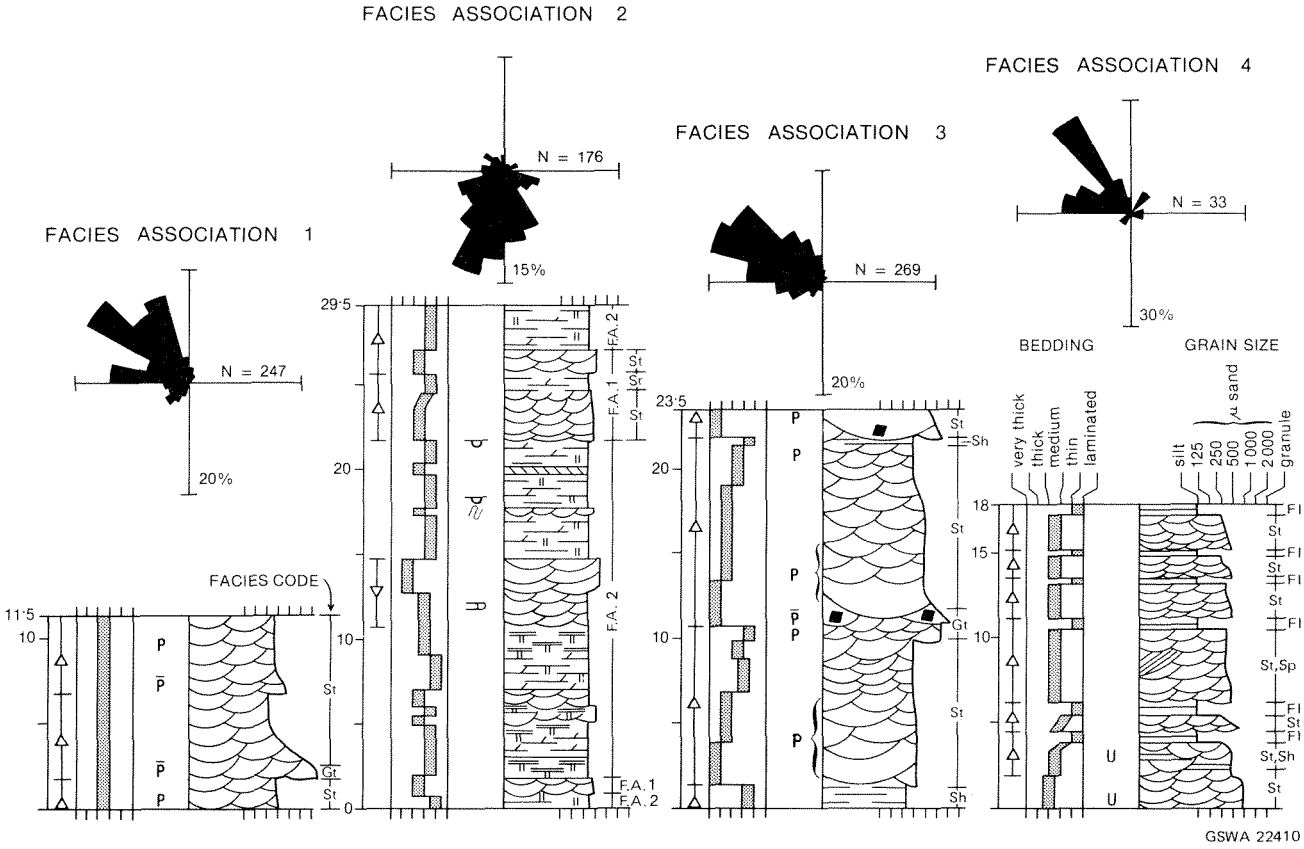

Figure 16. Representative detailed sections of Facies Associations 1 to 4, Tumblagooda Sandstone, after Figure 4 of Hocking (1981). Palaeocurrents are total for each association. For explanation of facies codes on right hand side of each section, see Table 1 of Hocking (1981), or Miall (1977, 1978). No section is presented for FA 5 due to nature of outcrop.

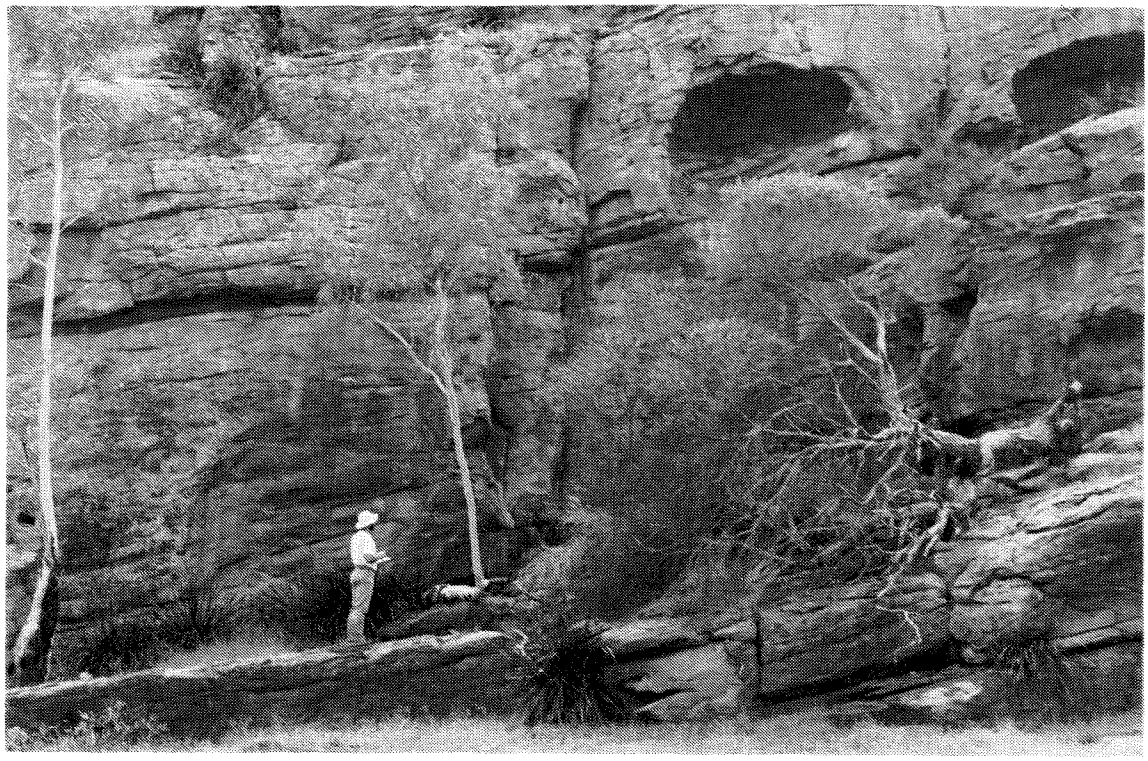

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Figure 17. FA 1 showing planar, laterally persistent, coset bounding planes separating cosets, 4 to 5 m thick. Near stream gauging station, top of section 1 on Figure 15.

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Figure 18. FA 2, 1 km upstream of The Loop. Horizontal stratified, bioturbated and planar cross-bedded facies are present, together with isolated small trough-shaped scours. Geological hammer at bottom centre.

The horizontally stratified facies consists of fine- to medium-grained, red and white striped sandstone, bedded on a 2 to 5 cm scale. Rippled surfaces are common, and locally show interference patterns. Bioturbation is also common, in the form of thin bioturbated intervals, discrete burrows, and various trails on bedding surfaces. Setulfs, dewatering pits and contorted bedding are also present at several localities. The facies commonly grades laterally into low- to very low-angle, asymptotically based cross-stratification.

The medium- to large-scale cross-stratified facies consists of asymptotically-based, low- to medium-angle, planar and trough bedded, fine- to medium-grained sandstone. Foresets are broadly unimodal at each locality, and show repeated reactivation: a single coset may persist for several hundred metres laterally, with reactivation every 20 to 50 m. Oversteepening and contortion (Hocking, 1981, Fig. 7A) are present but uncommon. The facies shows no bioturbation other than tracks on the tops of foresets.

The bioturbated-sandstone facies consists of intensely bioturbated, often gritty, medium-grained sandstone and is mostly developed as laminated to burrowed couplets up to 60 cm thick. These couplets consist of a sharp-based laminated sand overlain by progressively more bioturbated sand, with bedding destroyed for most of the couplet. Two sub-facies are present: parallel couplets, formed in horizontally bedded sandstone; and (less commonly) low-angle intersecting couplets, formed in low-angle cross-bedded sandstone.

The trough cross-bedded facies is generally present as a laterally persistent thin unit, only one or two troughs thick. It is composed of 20 cm deep scoop-shaped troughs of silicified medium-grained sandstone. It differs from FA 1 trough-cross-bedded sandstone, in that troughs are of roughly uniform size, and palaeocurrents are mostly southerly.

The sheet-sand facies consists of thin, laterally persistent, apparently structureless sheets of medium-grained, commonly silicified, sandstone. The sheets are generally less than 20 cm thick and commonly only 1 or 2 cm thick, and appear to be a reworked form of the trough-cross-stratified facies.

Of these facies, the first three comprise the bulk of FA 2, with the last two far less important. Ripple-laminated sandstone also occurs, and locally contains climbing ripples and eroded megaripple-shaped bedding surfaces. As a whole, FA 2 is characterized by the presence of bioturbation, generally thin bedding, and a grain size of fine to medium sand.

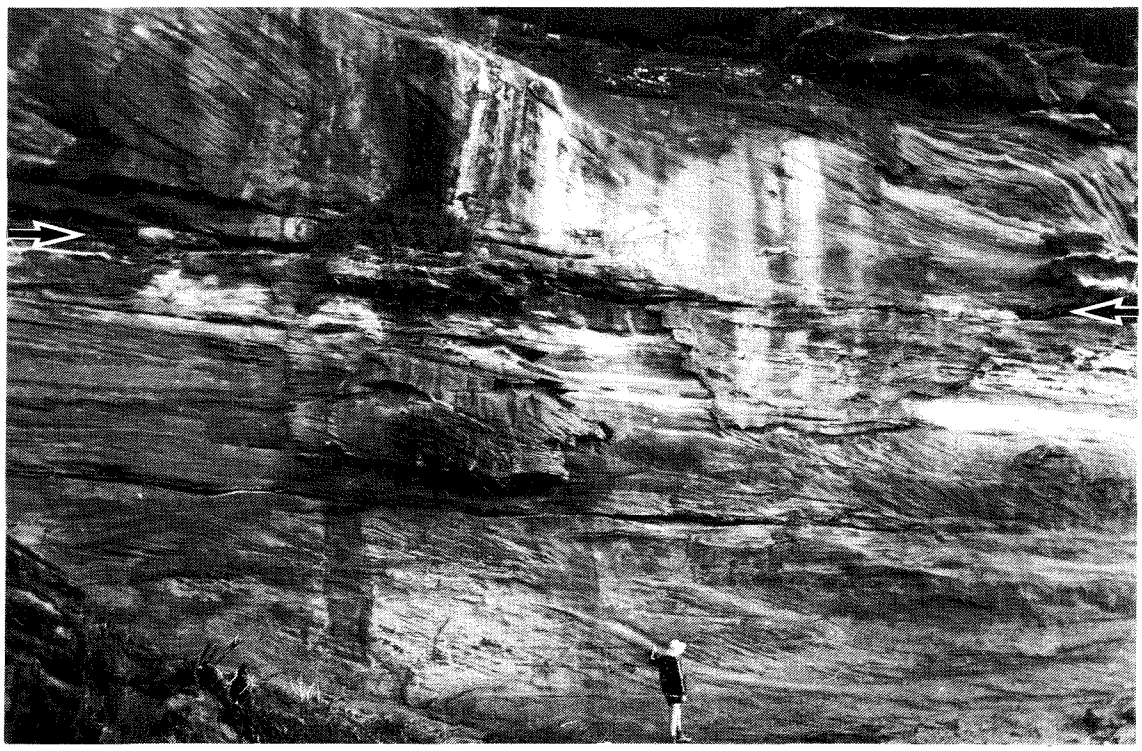

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Figure 19. FA 3, behind Bracken Point. Note very large foresets (person is 2 m tall) and cycles, which both fine and thin upwards. 1½ cycles are visible. Arrows mark base of cycle. Photograph taken near the base of section 15 on Figure 15.

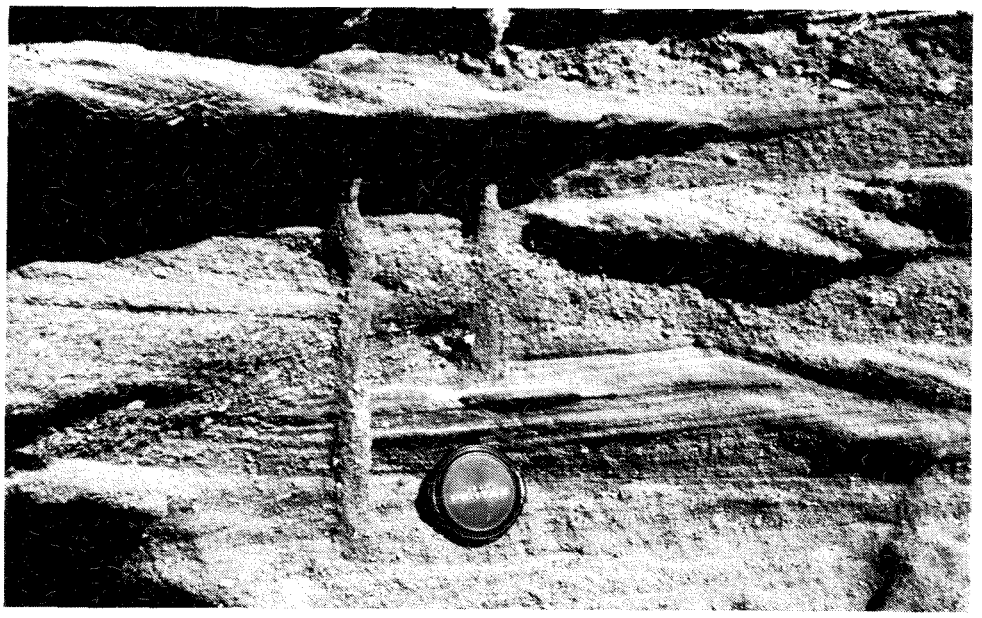

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Figure 20. ***Skolithos*** **in very coarse-grained sandstone and granule congolmerate (FA 3), base of Tumblagooda Hill. Lens cap 53 mm diameter.**

In the type section, there is a transitional interval of intercalated FA 1 and FA 2 sediments. This is followed to the northwest by almost wholly FA 2 sediments, with only minor FA 1 intercalations. The constituent FA 2 facies show a consistent, gradual change up section to the northwest. The proportion of the horizontally stratified and medium- to large-scale cross-bedded facies increases up section, and the bioturbated-sandstone facies decreases.

Facies Association 3 (FA 3): This is dominated by trough-cross-bedded, medium- to coarse-grained, poorly sorted, dark reddish sandstone, characteristically in fining-upwards cycles 10 to 15 m thick (Fig. 19). At the bases of cycles, troughs more than 4 m thick are locally present, and the sediment is very coarse-grained sandstone to granule or pebble conglomerate. Shaly and silty intraclasts are locally present. Palaeocurrents are unimodal to the west or northwest, and show a low scatter in individual horizons. Scattered *Skolithos* occur near the top of FA 3 (Fig. 20) above a distinctive pebbly sandstone marker horizon.

Facies Association 4 (FA 4): The lower part of FA 4 (FA 3a of Hocking, 1981) consists of fining-upwards cycles 0.5 to 2 m thick, from medium-grained sandstone to laminated, red, locally bioturbated and rippled, siltstone (Fig. 21), and was distinguished by Hocking (1981) as a lower energy variant of FA 3. It succeeds FA 3 relatively abruptly.

South of Red Bluff, the cyclic sediments are followed by medium- to coarse-grained, commonly poorly sorted, trough and tabular cross-stratified sandstone with abundant *Skolithos*. A similar facies is present at Pencell Pool immediately east of the Northampton Block (Fig. 22), and is probably a stratigraphic correlative of FA 4.

Facies Association 5 (FA 5): This occurs east of the Northampton Block, and consists of coarse- to very coarse-grained, poorly sorted and rounded, noticeably feldspathic sandstone grading to pebble and cobble conglomerate. Clasts are generally moderately to well rounded and are resistant rock types. Palaeocurrents are northerly to northwesterly. An unconformable relationship with rocks of the Northampton Block can generally be seen or reasonably inferred.

Distribution and thickness

Although the Tumblagooda Sandstone is only exposed on AJANA and GERALDTON, it has been intersected by petroleum-exploration and water wells as far north as WINNING POOL–MINILYA. Pendock 1 bottomed in the overlying Dirk Hartog Formation, as did Marrilla 1, on YANREY. This suggests that the Tumblagooda Sandstone may extend as far north as Exmouth Gulf.

GSWA 22415

Figure 21. FA 4, Red Bluff. 1 to 2 m thick fining-up cycles at base, overlain by thick subaqueous distributary deposits.

Johnstone and Playford (1955) measured a poorly exposed section, more than 3500 m thick, east of the Northampton Block along the Murchison River, but there may be substantial fault repetition which is unrecognized, because of the large gaps in outcrops. Elsewhere in the southern Carnarvon Basin, the Tumblagooda Sandstone is at least 1000 m thick and may be substantially more. In the Edel 1 area, for example, magnetic basement is at a depth of about 4000 m (Megallaa, 1980), which gives a possible thickness of over 3700 m (assuming the sequence below 354 m is Tumblagooda Sandstone). In the Quail 1–Wandagee 1 area, depth to magnetic basement (Megallaa, 1980) suggests that the Tumblagooda Sandstone may be only about 1000 m thick.

Gravity data suggest the Hardabut Fault moved during deposition of the Tumblagooda Sandstone (Playford and others, 1976), with a thicker section west of the fault on GERALDTON, although the sandstone is not disrupted. At several localities on GERALDTON, an unconformable contact between the Tumblagooda Sandstone and the Precambrian Northampton Block can be seen or reasonably inferred, but these localities cannot be correlated with the type section. This could be due to either the southern Northampton Block emerging as an exposed topographic feature, or to less deposition over the block. The second alternative, which implies that these localities are at the true stratigraphic base of the Tumblagooda Sandstone, is tentatively preferred because of the lack of garnet in the Tumblagooda Sandstone (the Northampton Block is garnet-rich) and the fact that palaeocurrents show no deflection around the block.

Some sediments mapped as Tumblagooda Sandstone by Playford and others (1970) north of Bindoo Hill, east of Binnu, and northeast of Nabawa at Nolba are probably not Tumblagooda Sandstone, but an unnamed pre-Late Carboniferous, post-Silurian unit. This is discussed in the section on unassigned Palaeozoic sediments.

Fossils and age

The Tumblagooda Sandstone contains a rich and varied ichnofauna (Öpik, 1959), but the only body fossils known are simple spores and microplankton of possible Late Silurian age (Balme, *in* Playford and others, 1975). The Dirk Hartog Formation, which conformably overlies the Tumblagooda Sandstone was dated as Late Silurian by Philip, (1969) and Öpik, (*in* Glenister and Glenister, 1957) which fixes the age of the bulk of the Tumblagooda Sandstone as Silurian. Playford and others (1975) noted that because of its thickness the Tumblagooda Sandstone could extend into the Ordovician: this is unlikely because mineralization, adjoining dolerite dykes, in the Northampton Block is dated at 434±15 Ma (J.

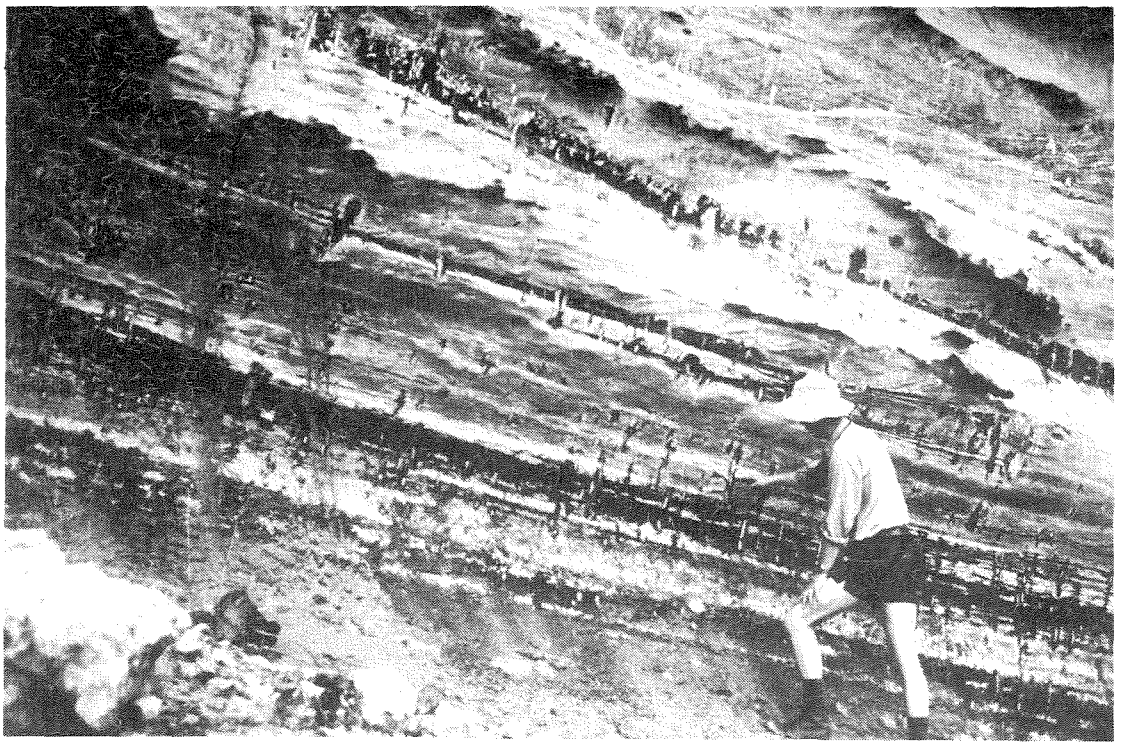

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Figure 22. ***Skolithos*** **and other trace fossils in silty horizontally bedded and trough cross-bedded sandstone, Pencell Pool. Dip is tectonic.**

Blockley, pers. comm.). There is no indication of dolerite intrusion, mineralization, or the prior passage of mineralizing fluids in the Tumblagooda Sandstone, suggesting that it is younger than 434 Ma.

Environments of deposition

The generally poor sorting, unimodal palaeocurrent pattern and bedding types of FA 1 and FA 3 indicate that they were deposited in a low-sinuosity, sheet-braided fluvial environment, with a source to the southeast. Conglomeratic sediments of FA 5 are a proximal variant of FA 1 or FA 3 and in part may be alluvial-fan deposits. In FA 2, ripple forms (which include flat-topped, interference, ladder, wave, current and climbing ripples) shrinkage cracks, trace-fossil forms and preservation, herringbone cross-stratification and palaeocurrent patterns indicate deposition in lower- to upper-intertidal conditions. This environment was dominated by longshore currents with lesser onshore currents. FA 4 was deposited in a protected interdistributary-bay environment, dominated by continental input. This is indicated by the westwards palaeocurrents and the common bioturbation.

In all outcrop areas, deposition appears to have commenced in a fluvial environment on a broad, sheet-braided plain (FA 1), grading upwards into a distal alluvial-fan environment east of the Northampton Block. A gradual transition to marine deposition (FA 2) followed, with interbedded fluvial and tidal sediments. The fluvial sediments in this transitional period appear to be broad distributary lobes prograding over interdistributary marine areas. Horizontally stratified sandstones were deposited on lower intertidal areas by waves, medium- to large-scale cross-bedded sandstones formed on lower to middle intertidal areas under current dominance, and bioturbated sandstone formed in upper-intertidal areas. The trough cross-stratified facies probably represents fluvial sands which have undergone minimal reworking into longshore and onshore megarippled sheets, because locally this facies can be accurately correlated with thin FA 1 fluvial beds. The sheet-sand facies may represent more thorough reworking and redistribution of the extremities of a fluvial-sand body by higher energy currents.

A sharp boundary separates FA 2 from the overlying FA 3, suggesting that an abrupt rejuvenation of the basin hinterland (probably by sudden movement on the Darling Fault) triggered off the high-energy sheet-braided fluvial deposition of FA 3. Like FA 1, deposition occurred in broad, large lobes. Sediment influx eventually diminished, resulting in the protected coastal environment in which FA 4 formed. The lower part formed in an interdistributary area, with intermittent food deposition. The *Skolithos*-bearing

sandstones at the top of the sequence in the coastal gorges are thought to be subaqueous distributary channels and sheets.

DIRK HARTOG FORMATION

Definition

The Dirk Hartog Formation does not outcrop. It was named the Dirk Hartog Limestone by McWhae and others (1958), but the sequence contains dolomite, shale, and sandstone, as well as limestone, and the name was amended in an unpublished report by Henderson and Shannon (1966). This was acknowledged and formalized by Playford and others (1975). The type section is in Dirk Hartog 17B well between 665 and 1404 m, and is almost entirely carbonate, dominated by dolomite. An evaporitic facies was named the Yaringa Evaporite Member by Playford and others (1975). Playford and others also suggested that the thick siliciclastic/carbonate couplet, above the carbonate facies of the Dirk Hartog Formation ("Unknown formation") in the Yaringa area, should be included in the Dirk Hartog Formation, but the rocks were placed in the Kopke Sandstone and Sweeney Mia Formation by Hocking (1985).

The Dirk Hartog Formation conformably overlies the Tumblagooda Sandstone and is overlain by the Kopke Formation with apparent conformity. Playford and others (1975) suggested that the basal contact with the Tumblagooda Sandstone, in Quail 1 and Wandagee 1, could be unconformable, as the change in lithology is abrupt. But in the absence of more definite evidence, the contact is assumed to be conformable, with at most a short hiatus in deposition. Relationships of recognized facies in the Dirk Hartog Formation between Pendock 1, Quail 1/Wandagee 1, and wells to the south indicate that the contact is time transgressive, with the lower part of the Dirk Hartog Formation in northern areas being laterally equivalent to the uppermost part of the Tumblagooda Sandstone to the south (Pearson, 1964). Tentative correlations within the Tumblagooda Sandstone support this: the uppermost part of the Tumblagooda Sandstone sequence at Pencell Pool is probably equivalent to the lowermost Dirk Hartog Formation in Kalbarri 1.

Yaringa Evaporite Member

The Yaringa Evaporite Member (Playford and others, 1975) corresponds to the informal "Unit B" of the Dirk Hartog Formation recognized in wells in the Shark Bay area (Henderson and Shannon, 1966; Continental Oil Company, 1968; Pendery and others, 1969; Kempin and Fujioka, 1973). The 76 m thick type section is in Yaringa 1 between 1195 and 1271 m. The Yaringa Evaporite Member contains several closely-spaced, laterally-extensive halite beds, and occurs almost in the middle of the Dirk Hartog Formation (Fig. 23).

The distinctive feature of the Yaringa Evaporite Member is the presence of 2 to 3 m thick halite beds though a 10 m bed is present in Yaringa 1. The salt beds appear to be reasonably pure halite, but sylvite is present and is a potential source of potash mineralization. The dominant lithology is dolomite, ranging from fine dolomitic mudstone to coarse lithoclastic peloidal grainstone. Silt is abundant in Yaringa 1 and claystone splits occur in Hamelin Pool 1. Anhydrite is common, as fracture fillings, beds, or nodule horizons. All units are typically red or brown.

The member has only been found in the Hamelin Pool area (Hamelin Pool 1, 2 and Yaringa 1). Some of the beds maintain their lateral continuity throughout this area, but marked thinning to the south in Hamelin Pool 2 suggests that the evaporitic-basin margin is nearby. There is no evidence of plastic flowage of the salt, although the present depth of burial (over 1000 m) would be sufficient to initiate flowage. The maximum thickness is in the type section (76 m) where the salt is also thickest (36 m).

Not enough is known about the spatial relationships of the evaporite minerals to be able to determine whether formation and deposition of the evaporite horizons took place in a desiccating basin or a barred basin, in the sense of Hsu (1972). The absence of the two top salt beds in Hamelin Pool 1 (presumably replaced by dolomite) and the greater thickness and number of salt beds in Yaringa 1 are suggestive of a barred-basin model with shallow-water evaporite deposition.

Lithology

The Dirk Hartog Formation is dominantly dolomite, with lesser limestone (Fig. 23). Siltstone occurs in minor zones and sandstone is restricted to thin beds, or as scattered grains within the carbonate. Evaporites are common: anhydrite is most widespread, and halite occurs in thick beds in restricted parts of the basin. The sequence is commonly brownish to reddish coloured, indicating very shallow, oxidizing conditions. However, in Pendock 1 the sediments are uniformly greenish-black, suggesting a substantially deeper basin with a constant reducing environment. Pyrite is present as nodules and fracture fillings in most wells.

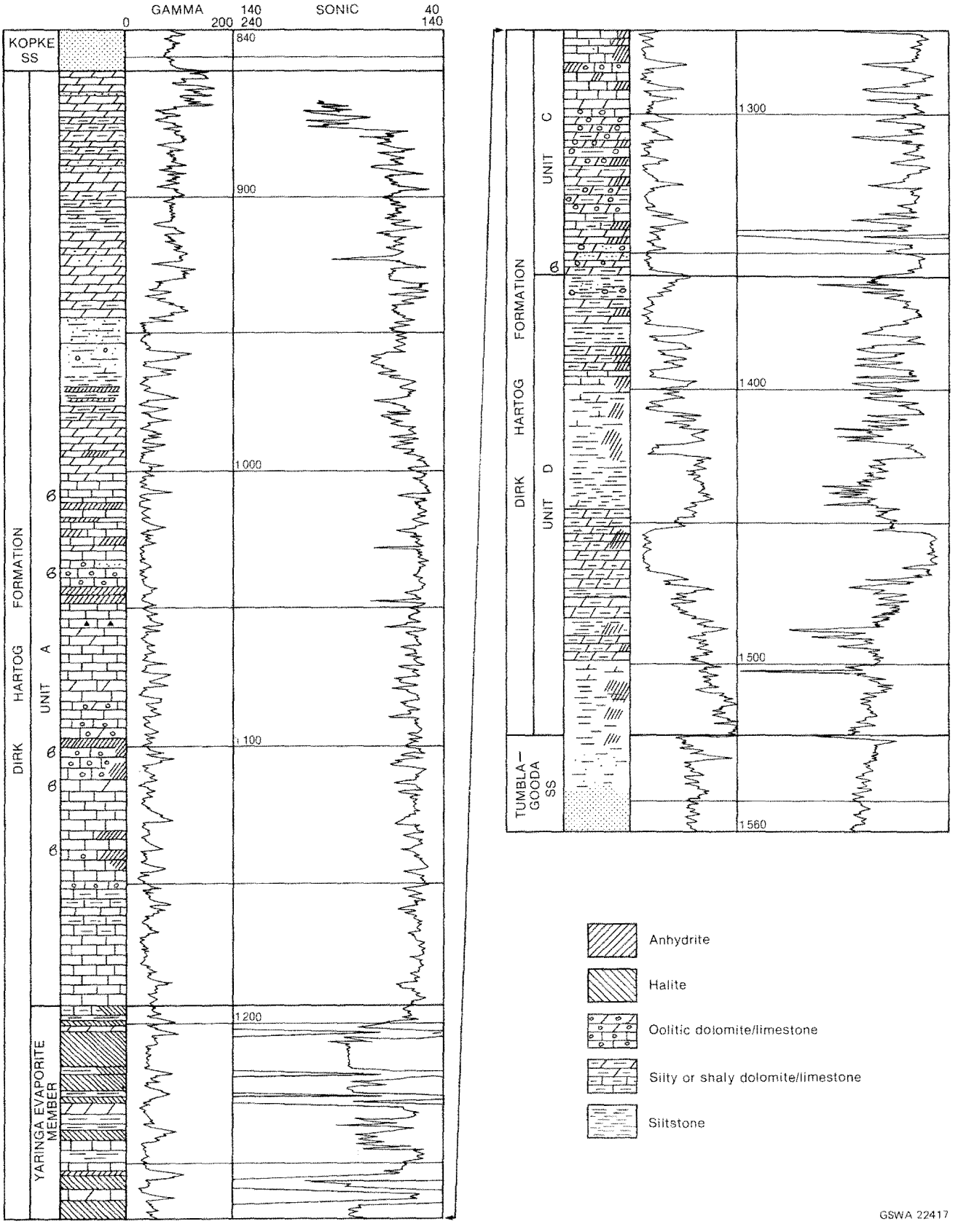

Figure 23. Dirk Hartog Formation in Yaringa 1, including type section of Yaringa Evaporite Member.

Most dolomite consists of very fine-grained dolomite rhombs. Bedding ranges from vague horizontal mottling to well-developed pin-stripe lamination. Peloidal dolomite packstone is also present. The peloids are usually structureless, and are faecal pellets or lithic fragments. There is minor dolomite with oolites and fossil fragments which clearly formed by the replacement of limestone. Lithic fragments of dolomite, dolomitic mudstone and limestone are abundant in the dolomites. The fragments locally have a micritic matrix, but more commonly there is a crystalline cement, which is probably of early diagenetic origin.

Limestone in the section also has a wide range of textural fabrics, ranging from mudstone to grainstone, indicating a range from quiet to turbulent water. Peloids and lithoclasts are as abundant as in the dolomite, and the very common oolites are obviously primary. The peloidal, lithoclastic and oolitic limestones are usually grainstones with up to 35% calcite cement, which shows that currents were effective in winnowing away muds, and that cementation took place at an early stage, before mechanical compaction. Fossils (molluscs and ostracods) are not common.

Siliciclastic sediments occur near the base and top of the formation as discrete units or enrichment zones resulting in argillaceous or sandy carbonates. Argillaceous rocks are commonly micaceous (indicative of a Precambrian provenance) and are usually oxidized to some degree. Sandstones are red-brown, usually well sorted, and dominantly fine grained.

Both anhydrite and halite are present. Halite mostly forms continuous beds of substantial thickness, but salt-enriched horizons with relic salt hoppers are present. Anhydrite is present mostly in nodules or fracture fillings; in places growth structures can be seen displacing sediments.

Distribution and thickness

The Dirk Hartog Formation has been intersected by wells as far apart as Kalbarri 1, Dirk Hartog 17B, Marrilla 1 and Pendock 1. It was deposited over most of the Gascoyne Sub-basin and in the western part of the Merlinleigh Sub-basin.

The thickest known intersection is 739 m in the type section, but this section has an eroded top. The unit at the top, Unit A, is somewhat thinner than in nearby wells, suggesting that a substantial part of it has been removed. Unit B, the Yaringa Evaporite Member, is thicker than in nearby wells, but it is not certain whether the basin was subsiding faster in the vicinity of Dirk Hartog 17B or whether the type section is complicated by repetitive faulting.

Individual beds show remarkable lateral persistence: comparison of gamma-ray logs in adjacent wells usually shows striking correlations. Similar sedimentary zones are easily recognized, and individual bed-by-bed correlations of units, only a couple of metres thick, can be made. The precision of correlations over 15 to 20 km (Hamelin Pool 1 to Yaringa 1, Wandagee 1 to Quail 1) is sufficient to reveal the presence of small faults, while correlations over nearly 100 km (Hamelin Pool 1 – Tamala 1) are possible on a bed-by-bed basis (Fig. 24). Approximately 20 m of sediment was deposited in the Yaringa 1 area before sedimentation commenced in Tamala 1, and approximately 15 m

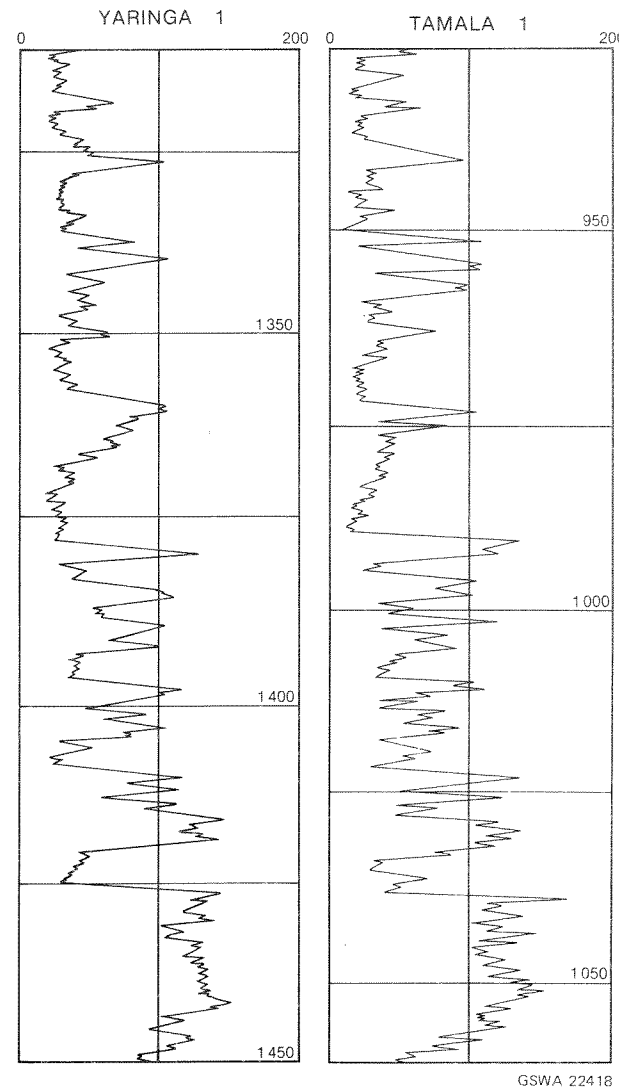

Figure 24. Gamma-ray logs of the Dirk Hartog Formation in Yaringa 1, and Tamala 1, 100 km apart, showing bed by bed correlations over long distances.

was deposited at Tamala 1 before sedimentation commenced at Kalbarri 1. It thus appears that, around Shark Bay, deposition of the Dirk Hartog Formation commenced in the Yaringa 1 area, and gradually extended west and south. On a broader scale, the lowermost unit of the Dirk Hartog Formation recognized in Wandagee 1 and Quail 1 appears to be absent in the Shark Bay area, indicating that deposition of the Dirk Hartog Formation lithofacies commenced earlier in the Wandagee area than in the Shark Bay area.

Fossils and age

Fossils are scarce because of the harsh depositional environment, and it has not been possible to determine the degree of diachroneity either within the formation or with underlying and overlying formations. The position is further complicated by the lack of fossils in the Tumblagooda and Kopke Sandstones. Fossils include gastropods, bivalves, brachiopods, ostracods, conodonts and acritarchs. Of these, Öpik (*in* Glenister and Glenister, 1957) considered one brachiopod (*Conchidium*) to be exclusively Late Silurian. Philip (1969) described the conodont fauna of the upper Dirk Hartog Formation, and suggested it was middle to late Ludlovian (Late Silurian). However, a very similar unit in the Canning Basin, the Carribuddy Group, is considered to be largely Early Devonian (Yeates and others, 1984; Brown and others, 1984; Lehmann, 1984), suggesting that the Dirk Hartog Formation may extend into the Devonian.

Environment of deposition

Deposition of the Dirk Hartog Formation generally commenced with an argillaceous sequence, after which there was a gradual diminution of the clay content with time. This was followed by nearly 200 m of dominantly carbonate deposition with periods of terrigenous inundation marked by thin highly argillaceous beds. In the Yaringa 1 area, the next 90 m contain evaporitic salt beds while elsewhere (and for an additional 250 m in the Yaringa 1 area) a carbonate section with only weakly argillaceous splits was deposited. The upper 100 m shows a return of argillaceous material before carbonate deposition had completely ended (Fig. 23).

The extreme lateral persistence of even thin beds is indicative of a very stable environment of deposition. From the sediments deposited, their textural features and fossil and mineral content, it is apparent that paralic conditions prevailed over the greater part of the basin for most of the time. The common red-brown colouration suggests an oxidizing environment, possibly with frequent subaerial exposure. The almost ubiquitous presence of anhydrite and general enrichment in magnesium (resulting in dolomite as the dominant carbonate) suggest shallow water and high evaporation rates. These features suggest that the depositional environment was a very wide, tidal rim on the eastern side of an epeiric sea, in which reasonably uniform subsidence produced laterally continuous beds. Highly saline conditions were for a while present in the Yaringa 1 area, possibly because of isolation and ponding, causing the formation of evaporites either by desiccation or precipitation from a highly saline brine. Repetition of these conditions produced several halite beds.

High-energy conditions occurred at times on this sea margin, because of the common intervals of lithoclastic limestones (now dolomites) within the sequence. Oolite shoals were also present, and the oolites from these areas were further spread by prevailing currents. The paucity of mudstone further highlights the moderate-energy regime, with most of the carbonate being grainstone or packstone, and micrite only present in the form of abundant peloids. Towards the west (Pendock 1) deeper water resulted in quieter, less oxidizing conditions, with a uniform sequence of dark argillaceous carbonate.

Economic aspects

There is some potential for economic potash mineralization in the Dirk Hartog Formation, primarily in the Yaringa Evaporite Member. The presence of sylvite in the evaporite sequence, even at a depth of over 1000 m was of sufficient interest to encourage Magellan Petroleum Pty Ltd to drill two wells (Hamelin Pool 1 and 2) to investigate the occurrence. The results of these wells established that a substantial evaporite basin existed in the area (Wells, 1980), and that a commercial concentration of potash mineralization could exist, but the cost of exploration was too high and the project was abandoned.

Some interest has been shown in the Dirk Hartog Formation for sulphide mineralization, but this remains unproven. Traces of pyrite are present throughout the unit, and suggest that it may be prospective if intersected in a position where it is more clearly a continental or sabkha deposit rather than being dominantly shallow-marine. A major drawback for any exploration in the Dirk Hartog Formation is the depth at which the unit occurs and the concomitant high costs of exploitation.

KOPKE SANDSTONE

Definition

The Kopke Sandstone (Hocking, 1985) is the siliciclastic sequence lying with apparent conformity on the Dirk Hartog Formation and overlain with apparent conformity by the Sweeney Mia Formation. Previously, it was referred to as "Unknown formation, unit B" by Henderson and Shannon (1966), and was included in the Dirk Hartog Formation by Playford and others (1975). The type section is the interval in Yaringa 1 between 326 and 855 m (Fig. 25).

Formation status is given to the Kopke Formation because, although little is known about its extent and possible variation, it represents a major phase of terrigenous siliciclastic deposition which is too large to be simply included within the Dirk Hartog Formation (a dominantly carbonate unit). The few cores of the Kopke Formation are indistinguishable from the Tumblagooda Sandstone and indicate a depositional environment quite distinct from the Dirk Hartog Formation.

Lithology

The Kopke Sandstone is composed predominantly of red or brown sandstone, which changes cyclically in size from very fine at the base to coarse in the middle, returning to fine at the top. The grains are subangular to angular and are moderately sorted; mica is a common accessory. Minor siltstone and shale are present, and are also predominantly brown. The red and white blotching which characterizes the Tumblagooda Sandstone is common, and in Core 5 from Yaringa 1 (355–358 m depth) clearly outlines bioturbation. Poorly sorted, coarse-grained, cross-stratified sandstones, indistinguishable from Facies Association 3 sandstones, in outcrop of the Tumblagooda Sandstone are present in Core 6 (450–456 m) and Core 9 (739–742 m).

Distribution and thickness

Complete sections of the Kopke Sandstone are known from three closely spaced wells in the Shark Bay area, Yaringa 1 between 326 and 855 m, Hamelin Pool 1 between 346 and 852 m and Hamelin Pool 2 between 295 and 761 m. The basal part of the unit was intersected by Tamala 1, between 398 and 425 m. Further to the north, both Wandagee 1 and Quail 1 intersected a sandstone sequence of Silurian age (McTavish, *in* Pudovskis, 1962) above the Dirk Hartog Formation, between

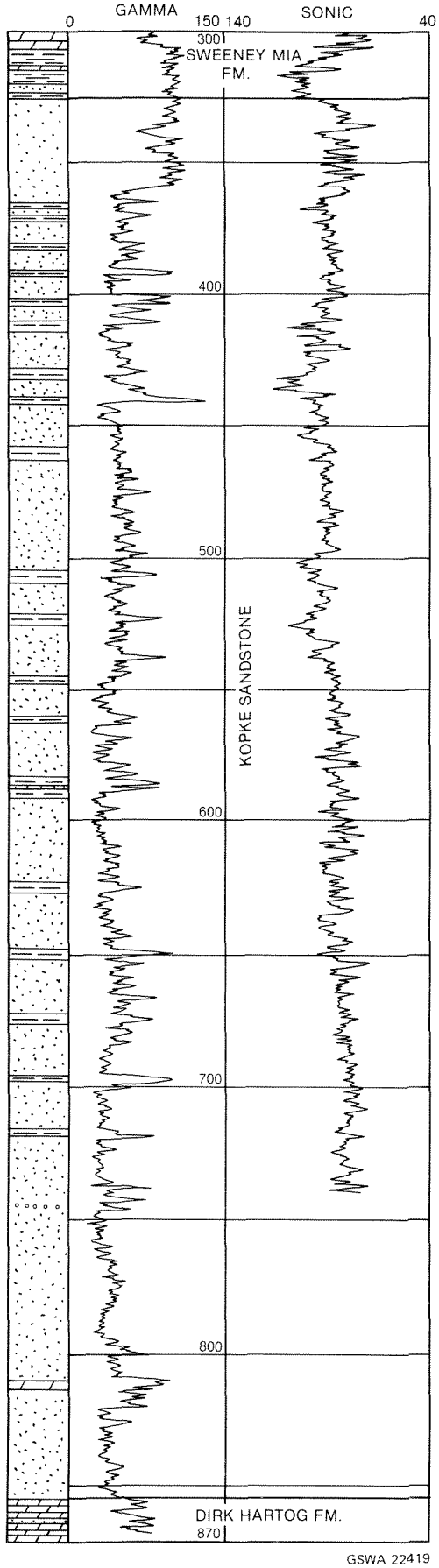

Figure 25. Type section of Kopke Sandstone in Yaringa 1. Lithology from original log.

278 and 399 m, and 3081 and 3205 m, respectively (Pudovskis, 1962; Pearson, 1964). This can be assigned to the Kopke Sandstone with reasonable certainty. Pendock 1 (Geary and Garrett, 1970; Genoa Oil N.L. 1970) intersected a sandstone sequence between 2191 and 2286 m within dolomites of the Dirk Hartog Formation but it is uncertain whether this correlates with the Kopke Sandstone, or is another sandy development at a stratigraphically lower level.

Fossils and age

The age of the Kopke Sandstone is determined largely by inference. It is apparently conformable above the Late Silurian Dirk Hartog Formation, and bears a close resemblance to the Tumblagooda Sandstone, and is therefore tentatively assigned to the Late Silurian. This assignation is supported by the Silurian Age, determined from conodonts, of the probable Kopke Sandstone in Wandagee 1 (McTavish, *in* Pudovskis, 1962). It may, however, be Early Devonian if correlation of the Dirk Hartog Formation with the Carribuddy Group is correct (see Dirk Hartog Formation section).

Environment of deposition

The depositional setting for the Kopke Sandstone is considered to be the same as that for the Tumblagooda Sandstone: very large lobes of sheet-braided fluvial sand prograding into a shallow epicontinental sea, with some reworking of sand by longshore-marine and tidal currents.

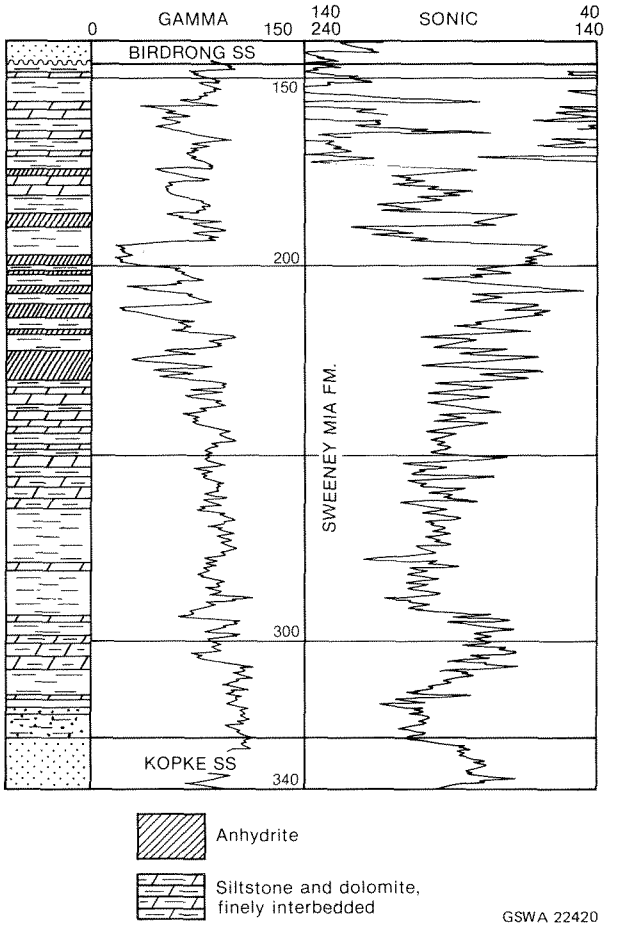

Figure 26. Type section of Sweeney Mia Formation in Yaringa 1. Lithology from original log.

SWEENEY MIA FORMATION

Definition

The Sweeney Mia Formation (Hocking, 1985) is the carbonate (dominantly dolomitic) sequence resting with apparent conformity on the Kopke Formation and overlain disconformably by younger sediments. The type section (Fig. 26) is in Yaringa 1 between 146 and 326 m. It was initially referred to as "Unknown formation, unit A" by Henderson and Shannon (1966), but later it was included in the Dirk Hartog Formation by Playford and others (1975). The sequence is given formation status because it is separated from the main carbonate sequence of the Dirk Hartog Formation by the Kopke Sandstone, and is sufficiently distinct from the Kopke Sandstone to warrant a different name.

Lithology

The Sweeny Mia Formation is an evaporite-carbonate suite similar to the Dirk Hartog Formation, but contains less carbonate; halite is also absent. The dolomite ranges in texture from saccharoidal to finely crystalline, with relic textures showing abundant lithoclasts. The colour is mostly orange-tan to grey. Extensive anhydrite beds (gypsum in Hamelin Pool 1; Continental Oil Co., 1968) interbedded with dolomite occur between 174 and 230 m in Yaringa 1, 241 and 262 m in Hamelin Pool 1, and 235 and 268 m in Hamelin Pool 2.

Distribution and thickness

The Sweeney Mia Formation is known from Yaringa 1 between 146 and 326 m, Hamelin Pool 2 between 197 and 325 m; and may be present in Pendock 1 between 1850 and 2192 m.

Age

The Sweeney Mia Formation is unfossiliferous. However, the apparently conformable sequence, together with the strong resemblance to the Late Silurian Dirk Hartog Formation suggests that it is also Late Silurian, possibly extending into the Early Devonian.

Environment of deposition

The Sweeney Mia Formation formed in similar conditions to the Dirk Hartog Formation, except that the presence of gypsum and anhydrite, rather than halite, indicates slightly less saline conditions (Kendall, 1979a).

The bedding structures seen in cores suggest that the evaporites are shallow-water subaqueous deposits rather than coastal sabkha or continental deposits (Kendall, 1979b). The environment of deposition is therefore tentatively suggested to have been a broad shallow basin with restricted circulation and, because of the shallow water depths, strongly oxidizing conditions.

Economic significance

The Sweeney Mia Formation contains evaporite beds, although they are not developed to the same extent as in the Dirk Hartog Formation, and they contain only anhydrite. Despite this, the potential of the formation should not be dismissed, and it should be considered a secondary target in any future evaporite-mineral exploration in the Silurian sequence.

CHAPTER 4

Devonian

Devonian sediments are exposed along the eastern margin of the Carnarvon Basin between about 24°30′S and 23°30′S, and have been intersected in the subsurface over a wide area north of 25°S. The sequence is almost 1500 m thick and has been divided into four conformable units, the Nannyarra Sandstone, the Gneudna Formation, the Munabia Sandstone, and the Willaraddie Formation. Deposition began in the Givetian and continued into the Late Devonian.

The Nannyarra Sandstone is a transgressive, siliciclastic sequence which oversteps the Silurian sequence. The existing palaeotopography controlled the shape of the basin margin, and the Nannyarra Sandstone accumulated in topographic lows by the concentration of terrigenous debris. This sediment source was soon depleted, and the carbonates of the Gneudna Formation were deposited on a wide shallow-marine shelf.

Tectonism towards the end of the Frasnian rejuvenated the hinterland and led to braided-fluvial deposition (the Munabia Sandstone). This graded laterally into, and was followed by, alluvial-fan deposition (the Willaraddie Formation) in the Williambury area.

NANNYARRA SANDSTONE

Definition

The Nannyarra Sandstone ("Nannyarra Greywacke" of Condon, 1954; amended by Hocking and others, 1980) is a discontinuous quartz and lithic wacke at the base of the Devonian sequence. In outcrop, the formation is markedly unconformable on Precambrian rocks. It is conformably overlain by and laterally gradational into the Gneudna Formation. In the subsurface it rests unconformably on Silurian sediments. The 57 m thick type section (Fig. 27A) is southeast of Williambury homestead.

Lithology

The Nannyarra Sandstone is a sandy siliciclastic sequence with only minor silty or argillaceous intervals. The sandstone ranges from very coarse to very fine grained, but is commonly medium grained. Grains are usually subangular to rounded with lesser very angular grains, although quartz grains commonly have their shape drastically altered by solution or overgrowths, and the shale and schist lithic fragments are usually plastically deformed. Muscovite and feldspar are common, with minor tourmaline and zircon, which suggests a Precambrian source. The sequence is mostly horizontally bedded, and fining-upward cycles about 2 m thick are locally present. Cross-bedding is minor. Sets of planar cross-bedding up to 2 m thick occur, but more commonly foresets are curved and only decimetres high. Rare low-amplitude sinuous ripples are also present.

A basal-lag conglomerate locally occurs on the Precambrian unconformity. It is composed of subangular milky-quartz clasts from pebble to cobble size, in a micaceous, arkosic gritty matrix.

Siltstone is uncommon and has the same range of components as sandstone, with quartz predominating and lesser mica, feldspar and lithic fragments. An argillaceous matrix is also usually present. Claystone outcrops poorly, with mud cracks preserved in the soles of some sandstone beds.

The formation can usually be divided into two facies, a lower oxidizing facies in which the sediments are dominantly red or brown, and an upper, more reducing facies where the sediments are dominantly green. In outcrop, leaching or concentration of iron may mask this subdivision to some degree, but it is well expressed in exploration wells (*e.g.* Quail 1).

Poorly sorted, trough cross-bedded, gritty and silty sandstone is locally present at the base of the Nannyarra Sandstone, most notably southwest of Lyndon homestead. This forms a distinct lithotype which has not undergone winnowing before or during deposition.

Distribution and thickness

The Nannyarra Sandstone has a highly variable thickness and discontinuous distribution. The formation occurs in embayments, or topographic lows, in the Precambrian, such as in the area of the type section, where the deepest part of the embayment contains over 50 m more strata than the type section itself, and less than 5 km to the north or south, the Gneudna Formation rests directly on the Precambrian. In this fashion, the Nannyarra Sandstone is discontinuously present in the belt of Devonian outcrop between Lyndon and Mount Sandiman. The thickest section in outcrop is about 120 m, east of Woodcock Bore: Condon's (1965b) suggestion that this value was inflated is incorrect. The Nannyarra Sandstone has also been identified in Quail 1 and Wandagee 1 (slightly more than 120 m), in Pendock 1 (185 m), and in the Robe River embayment, at the base of Echo Bluff 1.

Fossils and age

Apart from palynomorphs and conodonts found in exploration wells, no body fossils are known from the Nannyarra Sandstone. However, bioturbation of sediments is not uncommon, and trace fossils have been found but not studied.

The Nannyarra Sandstone grades into the overlying Gneudna Formation, which is of Givetian to Frasnian (Middle to Late Devonian) age, and in Pendock 1 a microflora from a core in the Nannyarra Sandstone is indistinguishable from that in the Gneudna Formation (Geary and Garret, 1970). The Nannyarra Sandstone is therefore considered to be Givetian. Early Devonian and Silurian identifications in Pendock 1 and in Wandagee 1 (Pudovskis, 1962) are assumed to be either misidentifications or reworked material.

Environment of deposition

The Nannyarra Sandstone is a coastal deposit associated with a shallow-marine transgression. Most of the unit consists of horizontally bedded sandstone with, in places, common 3–5 cm thick lenticular beds of arkosic grit. This suggests a beach environment with sheets of coarse sediment periodically brought in by floods and partially redistributed. A series of 1.5 to 2 m thick fining-upward cycles from medium to fine sand, with slightly scoured bases, may represent tidal-channel fill in a slowly subsiding basin. The finer grained sands are locally bioturbated and, rarely, have a rippled upper surface with a thin mud drape showing desiccation cracking.

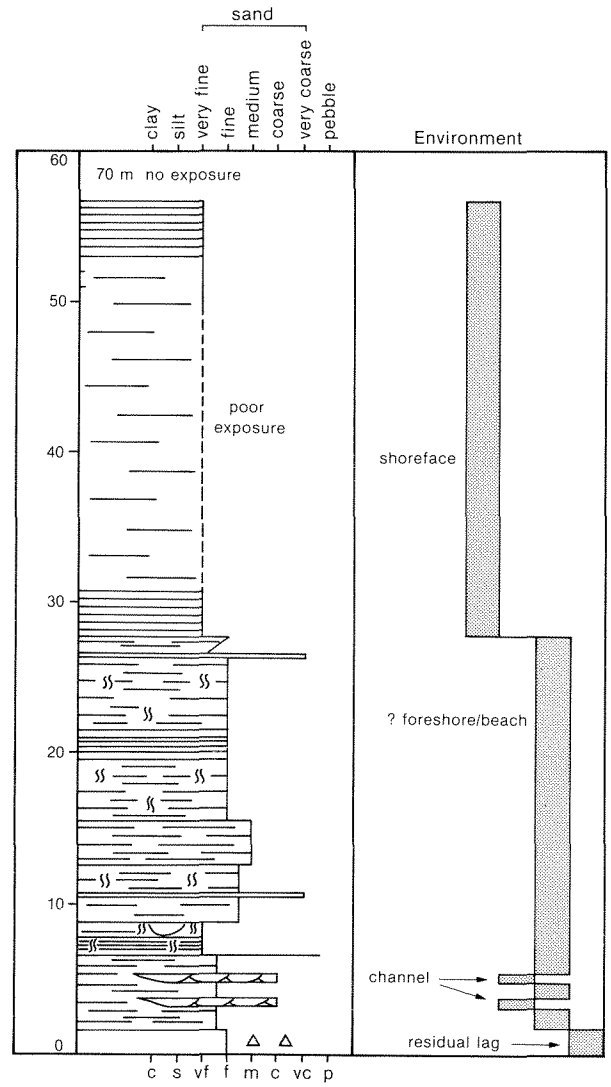

Figure 27A. Type section of Nannyarra Sandstone, Williambury Station. Sequence is silty throughout. Above 57 m, there is 70 m not exposed which is assigned to the Gneudna Formation. Between 127 m and 150 m, sequence is still dominantly sandstone although part of the Gneudna Formation.

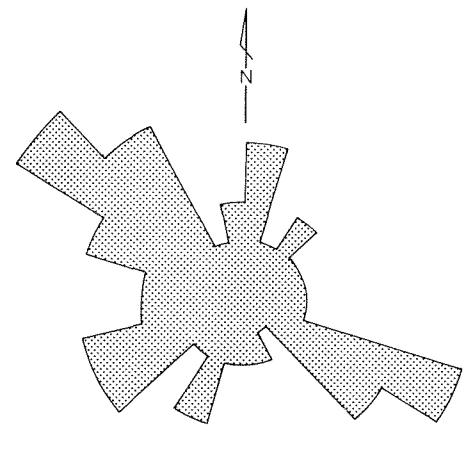

Figure 27B. Composite palaeocurrent rose for the Nannyarra Sandstone. 83 measurements, mostly from cross-bedding, 20° sectors.

East of Woodcock Bore, bottom slopes were steeper and shoreface deposits are present. Beach and foreshore sediments appear as thick planar cross-bedded units while upper shoreface sediments are finer grained and contain abundant, shallow, trough cross stratification.

Water depth gradually increased during deposition. This is shown by the change from oxidized sediments, in the lower part of the Nannyarra Sandstone, to more reduced sediments in the upper part, and an overall upwards decrease in grain size. The oxidized lower part probably was deposited on a wide shallow well-aerated beach while the upper part formed in deeper, less oxidizing, conditions.

The poorly sorted basal sandstones and lag conglomerates found at some localities are fluvial and residual deposits, which were not reworked by the onlapping transgression because they were either in very pronounced topographic lows or in protected positions.

A composite rosette of 83 palaeocurrent measurements for the formation has a vector mean to 300°, and a polymodal distribution: the northwest direction is part of a northwest–southeast preference, while two oblique submodes are nearly normal to this trend (Fig. 27B). The strongest trend is here considered to be the palaeocoastline, the others being channel trends normal to this.

GNEUDNA FORMATION

Definition

The Gneudna Formation is a mixed-carbonate and siltstone sequence, with some interbedded sandstone near the base and top. Teichert (1949) named the "Gneudna Limestone" and established its Devonian age. However, Condon was the first to define the limits of the formation, and in so doing included a considerable proportion of siliciclastic sediments, necessitating a change of name to the Gneudna Formation (Condon, 1954). The type section adjoins the Nannyarra Sandstone type section, southeast of Williambury homestead, and was shown in detail by Condon (1965b, Fig. 14).

The Gneudna Formation has a gradational contact with the underlying Nannyarra Sandstone, the boundary being placed at the first limestone bed. Where the Nannyarra Sandstone is absent (*e.g.* north of Mount Sandiman homestead) the formation lies with angular unconformity on the Precambrian basement. The upper boundary with the Munabia Sandstone is also transitional, and has been picked at the last hard limestone. Because of the interfingering relationships of the boundaries, a small degree of diachronism is undoubtedly present from location to location.

A possible reefal development was intersected over a thickness of 320 m in Pendock 1 and defined as the "Point Maud Formation" by Geary (1970), but Hocking, Williams, Lavaring, and Moore (1983) gave this member status within the Gneudna Formation. The section is shown in Figure 28.

Point Maud Member

The Point Maud Member is a "reefal" facies within the Gneudna Formation, and has its type section in Pendock 1 between 1289 and 1609 m (Fig. 28). The "Point Maud Formation" was erected by Geary (1970), who believed that the interval between the depths 1289 m and 1665 m "forms part of a reef complex, and is a completely different facies from the shelf carbonates and clastics of the Gneudna Formation" (Geary, 1970, p. 15). However, although no reefal structures have been found, abundant corals and stromatoporoids occur at some horizons in other parts of the Gneudna Formation, and the basal part of the unit is very similar to Gneudna Formation above it. This led Hocking, Williams, Lavaring and Moore (1985) to revise the definition of the unit, amending its status to Point Maud Member.

The lithology is very uniform, consisting of white, brown and grey, very finely to coarsely crystalline dolomite with stromatoporoids (including abundant *Amphipora*) and corals, and thin beds of green to dark-brown shale. The dolomite has vuggy porosity, often partly filled with calcite.

The Point Maud Member is known from Pendock 1 and may be present in Quobba 1. Thin (tens of metres) dolomitic horizons occur elsewhere in the Gneudna Formation, but cannot be definitely correlated with the member. The most probable depositional environment appears to be a reefal development (probably platform facies) within the Gneudna Formation in a shelf-break setting.

Lithology

Condon (1965b) considered that about half of the type section was carbonate, the remainder being sandstone (40%) and siltstone (10%). Most of the siliciclastic sediments occur in the transitional upper and lower parts, and outcrop poorly, whilst

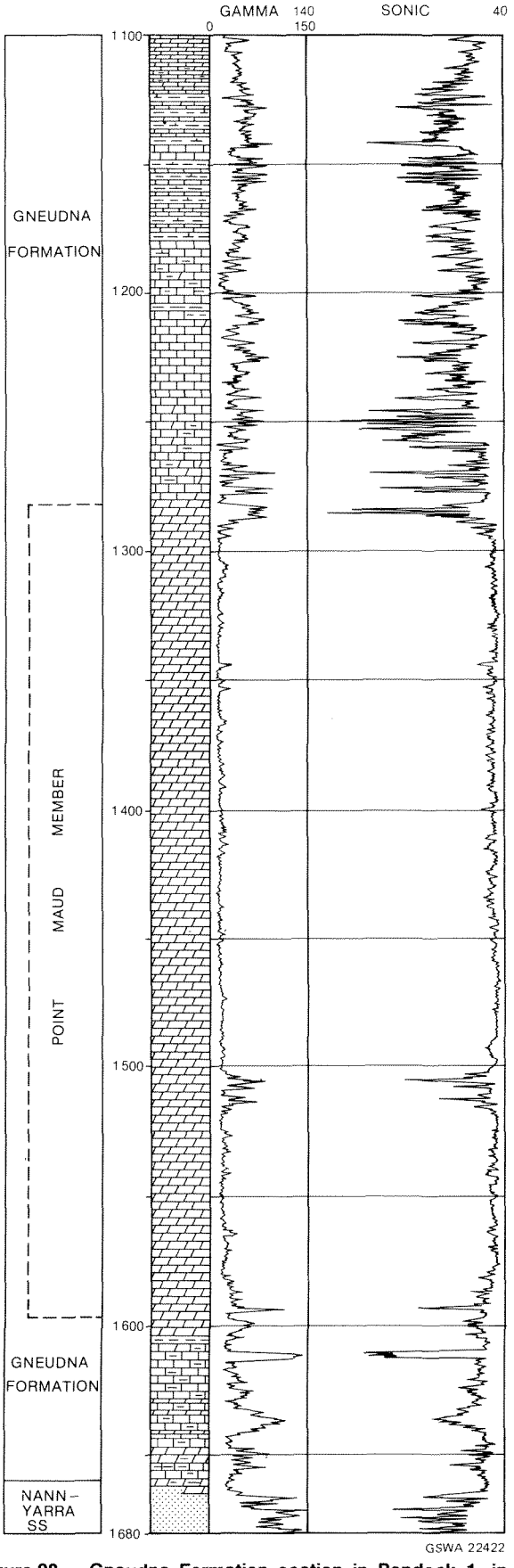

Figure 28. Gneudna Formation section in Pendock 1, including type section of Point Maud Member. Note uniform log response of Point Maud Member compared to remainder of Gneudna Formation.

the middle portion is dominantly carbonate, and Condon may have overestimated the volume of siliciclastic sediment.

The carbonate is largely limestone, but dolomitization has occurred in a number of zones, mostly in the upper third of the formation, where nearly all carbonate is now dolomite. Irregular, preferential, partial dolomitization also occurs near the base of the carbonate sequence.

The most common lithotype is a bioturbated bioclastic packstone (Figs 29, 30). Most of the macrofauna is comminuted to a shell hash, although small fossils such as ostracods and calcispheres are commonly intact. Bedding is on a decimetre scale, and is commonly obliterated by bioturbation, resulting in massive beds up to 2 m thick in which unbioturbated areas are enclosed in a bioturbated matrix. This, with stylolitization, produces typically nodular outcrop. Laminated to burrowed couplets are common. Except for brachiopod, calcisphere, crinoid, and some ostracod fragments, fossils are usually totally recrystallized to spar.

Packstone grades into grainstone, in which micrite is only present in "current shadows". Grains commonly have a rim of needle-like calcite which pre-dates coarser, cavity-filling spar and suggests that the absence of micrite is a depositional effect due to winnowing. Spar cement forms about 30–40% of the rock (Fig. 31). Bedding is generally on a decimetre scale, with local cross-bedding and graded bedding.

Packstone also grades into wackestone and lime mudstone. Neither is common, and presumably formed in protected areas such as local hollows. The lime mudstone occurs in a laterally extensive interval, 10–15 m thick, and is finely laminated and fissile. The mudstone is composed of very fine peloids and micrite, and a poorly developed fenestral fabric is locally present.

Boundstone is not common in Gneudna Formation outcrop, but corals, stromatoporoids and algae are present, and locally abundant. Algal fronds are present as clastic debris, and algal coatings (bindings) are common on other fossil fragments. Algal mats occur locally.

A common diagenetic history appears to start with the early formation of a micritic rim around aragonite grains, followed by the solution of the aragonite. The dissolved carbonate then formed a fine druse around the micritic rims and other calcite or magnesian calcite grains, cementing the grains together. Later, calcite completely filled the intergranular porosity and finally the intragranular porosity. The commonly very high spar content

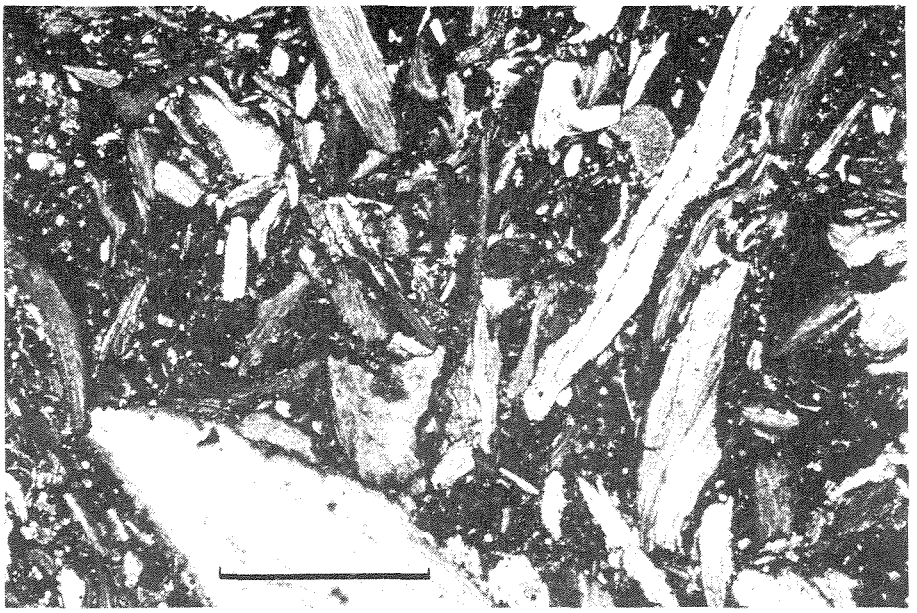

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Figure 29. Micrograph of brachiopod packstone, Gneudna Formation. Brachiopod fragments are broken in a silt to mud matrix. Very fine detail is still preserved in fragments. Scale bar is 2.0 mm.

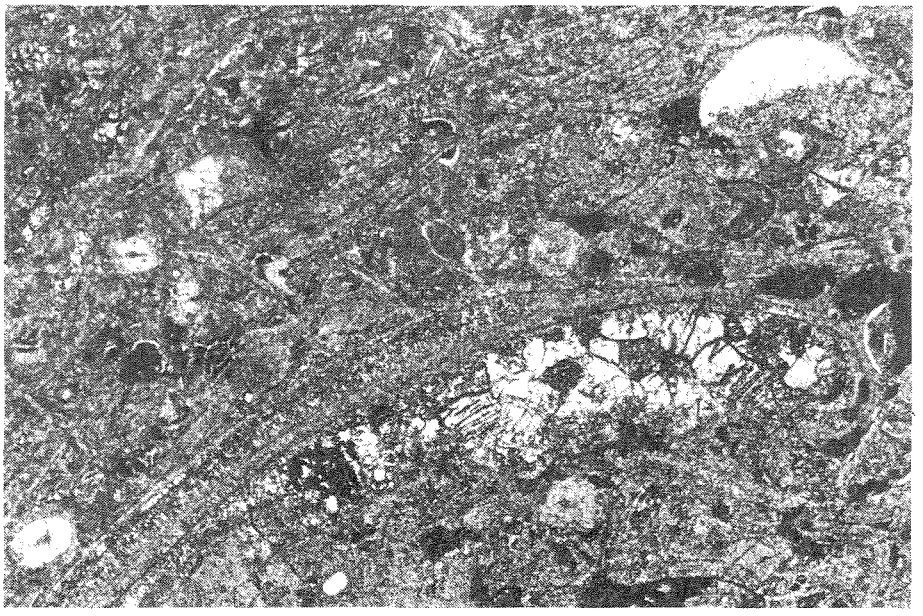

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Figure 30. Micrograph of mollusc packstone, Gneudna Formation. Shows early micritic rim around aragonite, solution of aragonite, and deposition of fine drusy rim before coarse calcite spar filled remaining voids. Some echinoderm fragments retain very fine structure.

suggests early cementation, as little evidence of compaction of the grains can be seen (Fig. 31). Interpenetration of grains usually occurs along infrequent small-scale stylolites. Syntaxial overgrowth of echinodermal material can rarely be seen, and ranges from thin rims to thick deposits with excellent crystal outline.

Microscopic fractures are present. Some are infilled with micritic mud and pre-date lithification, but others traverse grains, while some have a short lateral extent and a wedge-shaped cross-section and are related to shrinkage of the beds.

Distribution and thickness

The Gneudna Formation outcrops along the eastern margin of the Carnarvon Basin between Walter Well, on Towera Station, and Mount Sandiman homestead, a distance of more than 100 km. There is fault repetition of the formation, forming three outcrop belts.

Because of the gradational nature of the upper and lower contacts, it is very difficult to measure the true thickness of the formation. The type section is about 520 m thick, but of this the lower-

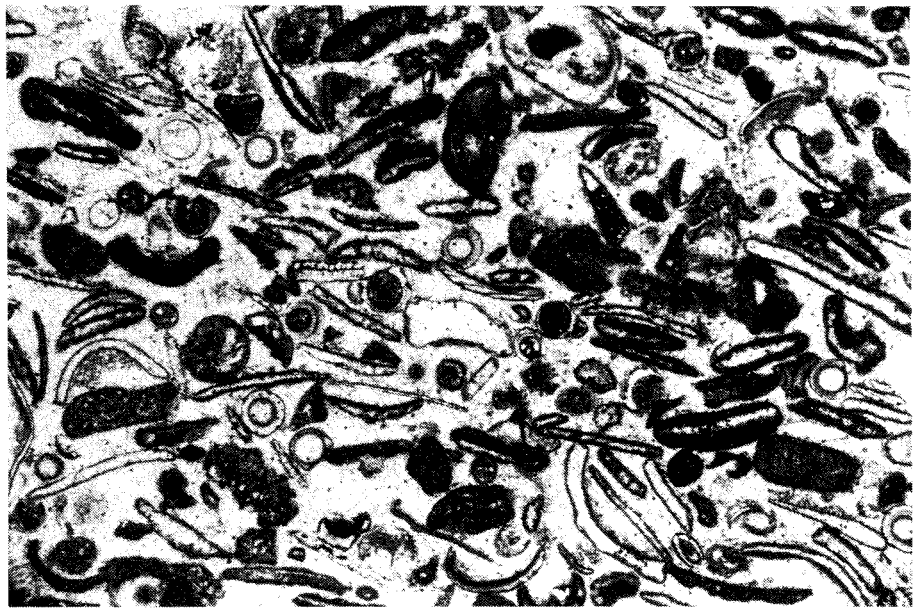

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Figure 31. Micrograph of calcisphere-ostracod bioclastic grainstone, Gneudna Formation. Calcisphere and "*Cryptophyllus*" type ostracods retain shell detail while other organic fragments are represented only by a micritic rim. High spar-cement content and lack of deformation suggest early cementation.

most 70 m is poorly exposed, and the next 20 m could equally well be placed in the Nannyarra Sandstone, as it is in large part quartzose sandstone to siltstone. There is not as much variability in thickness as Condon (1965b, p. 45) suggested: he proposed that variations in sediment thickness were due to basement ridges and depressions. This is incorrect, as the structures are post-depositional. However, there may be a general northwards thickening.

In the subsurface, the Gneudna Formation has been recognized in wells and bores north of 25°S. It thickens to the north and west, with thicknesses of 341 m in Quail 1, 558 m in Pendock 1, and possibly more than 1191 m in Rough Range 1. Condon (1965b) thought that the sequence in Rough Range 1, between 3261 m and 4452 m (total depth) correlated with the Willaraddie Formation, but we accept the opinions of both McWhae and others (1958) and Playford and others (1975), who considered this interval to be Gneudna Formation.

The northernmost intersections of sediments which correlate with the Gneudna Formation are in the Robe River embayment, in Peedamullah 1 and Echo Bluff 1. In Peedamullah 1, the sequence consists of dolomitic sandstone with lesser siltstone and dolomite, and in the lower part contains an abundant, well preserved microflora (Cowan, 1968).

Fossils and age

The Gneudna Formation is very fossiliferous, but most larger fossils have been comminuted to a shell hash, and many smaller fossils are preserved only as micritic outlines filled with equant spar. Fossils present include brachiopods, bivalves, gastropods, cephalopods, tentaculitids, corals, stromatoporoids, calcareous and blue-green algae, conodonts, fish remains, and palynomorphs. Ostracods are extremely abundant, as are calcispheres at some horizons. Fragmented echinoderm remains (both pelmatozoans and eleutherozoans) are also common. An unpublished thesis by Dring (1980) provides a comprehensive overview of the palaeontology of the Gneudna Formation. Spores were described by Balme (1962), and Playford (1981, 1983) and acritarchs by Playford and Dring (1981).

The formation was dated as late Givetian to early Frasnian on the basis of conodonts by Seddon (1969) and of corals by Hill (1954). However Playford and Dring (1981) regarded it as probably wholly early Frasnian, based on acritarchs and a review of other work on Western Australian Devonian sequences.

Environment of deposition

A depositional model for the Gneudna Formation is shown in Figure 32. Deposition appears to have been in an epeiric sea/ramp environment,

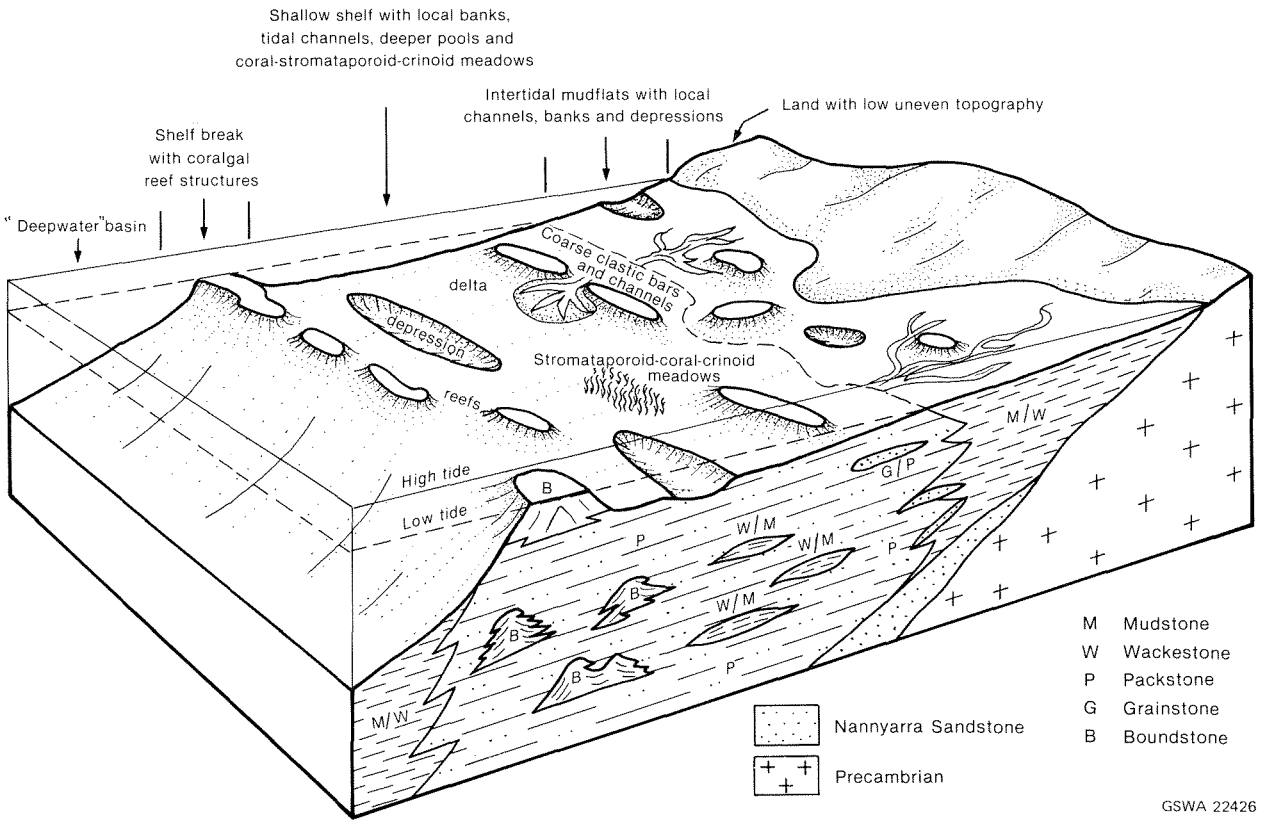

Figure 32. Depositional model for the Gneudna Formation. Three zones are present in outcrop and subcrop. The intertidal zone is mainly mudstone and wackestone, with coarser material in tidal channels and banks and finer material in depressions. The shallow shelf zone is mainly bioturbated packstone deposited at a water depth of up to 10 m. Coarse grainstone occurs in bars and small tidal deltas. Finer sediment accumulated in depressions and in quiet zones of stromatoporoid-coral-crinoid meadows. The shelf-break zone may have been intersected in Pendock 1. Deep-water basinal sediments have not been found.

with most of the type section forming in the wave-affected part of the ramp, although deposits ranging up to intertidal are present.

The intertidal zone was a laterally extensive calcareous mudflat, with local banks, hollows and channels. It probably extended down-dip for several kilometres because of the gentle palaeoslope. Most wave energy was dissipated on the fringing shallow shelf, producing a low-energy environment dominated by mud deposition from suspension. Other than peloids and salinity-tolerant organisms (which probably inhabited shallow ponds), coarse carbonate material was lacking. Both terrigenous material and dead marine organisms were periodically swept onto the mudflats, with fragmented-nautiloid tests commonly the only fossil in argillaceous horizons. This environment was dominant for a longer period in the eastern outcrop belt near Munaballya Tank, as the nodular packstone lithotype (which formed in the shallow-shelf zone) is only present in the upper part of the section.

Most of the Gneudna Formation was deposited in the shallow shelf zone, characterized by shallow water and moderate- to high-energy conditions, resulting in the deposition of bioturbated bioclastic packstone. Bars formed in this zone and concentrated energy into small areas, with quiet sheltered areas immediately behind the bars. Coarse grainstone was deposited in the bars and channels, and wackestone in the landward, sheltered areas. Wackestone and even mudstones were deposited in deeper depressions on the shelf, and stromatoporoid/coral/crinoid meadows locally absorbed sufficient wave energy to allow deposition of fine-grained sediments. In outcrop, all coral and stromatoporoid accumulations are death assemblages.

The shelf-break zone is not seen in outcrop, but may be represented by the Point Maud Member in Pendock 1. The thickness of the member, 320 m, suggests that reefoid accumulation in a shelf-break setting may have occurred.

Reef complexes of the same age as the Gneudna Formation are present in the Canning and Bonaparte Basins, but the Carnarvon Basin may have been too far south for such structures to have developed on a large scale.

MUNABIA SANDSTONE

Definition

At an early stage in the mapping of the Carnarvon Basin, Teichert (1949) defined the Munabia Sandstone as the siliciclastic sequence between the carbonate-dominated Gneudna Formation and Moogooree Limestone. Further mapping (Condon, 1954) resulted in the division of this sequence into two formations. The Munabia Sandstone is now recognized as the dominantly mature-sandstone sequence which conformably overlies and interfingers with the Gneudna Formation, and conformably underlies and interfingers with the dominantly immature-sandstone and conglomerate sequence of the Willaraddie Formation. The type section (Condon, 1965b, Fig. 19) is southeast of Williambury homestead.

Lithology

The formation consists of sandstone, with minor claystone, conglomerate and dolomite. The sandstone ranges from very fine to very coarse grained, with the majority medium grained. Scattered granules occur locally. It is usually moderately sorted with little argillaceous matrix, though highly argillaceous sandstone is associated with horizons of pebbly sandstone. The grains are subangular to subrounded, but grains commonly have an authigenic overgrowth resulting in a subangular appearance. The highly argillaceous beds are invariably friable resulting in poor outcrop. Quartz is the dominant (50–90%) sandstone component, with lesser feldspar and lithic fragments (including chert). Accessory minerals include variable amounts of mica, tourmaline, apatite, and zircon. Orthoclase, microcline and oligoclase feldspars have been recognized, with albite overgrowth of some grains. Glauconite is present at some stratigraphic horizons.

Two sandstone facies can be distinguished, based on bedform and colour: brown, bioturbated, thin-bedded sandstone, and red or white, thicker bedded sandstone. The brown-sandstone facies is commonly horizontally bedded, with some small-scale cross-bedding (in places herringbone), common flaser and lenticular bedding, and teepee-type expansion structures. Sub-parallel to curved ripples are present and locally show desiccation impressions. Irregular trails, burrows, and living and resting structures occur. The red and white sandstone is thicker bedded and characteristically trough cross-bedded. Troughs are up to 3 m wide and 30 cm deep and locally show complex reactivation. Planar foresets up to 2 m high are common and in many places are contorted due to slumping and dewatering. Small-scale planar cross-bedding is also common. Dewatering structures locally disrupt bedding (Fig. 33).

Claystone is rarely seen in outcrop, although clay intraclasts are present within sandstones. The claystone is silty and micaceous.

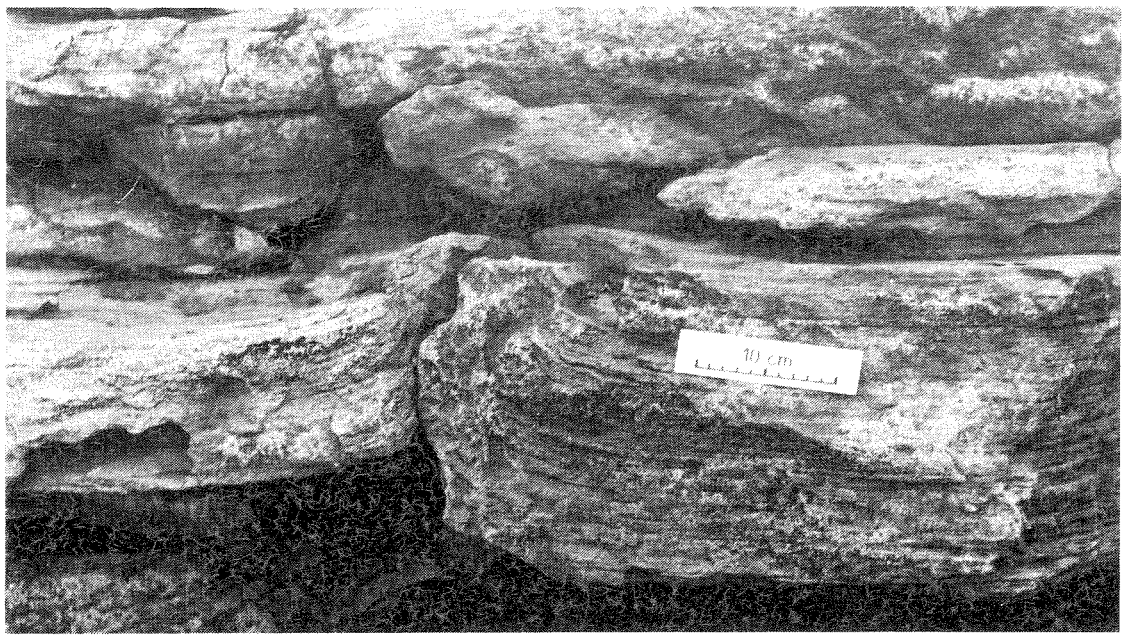

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Figure 33. Cross-section through sand volcano, lower Munabia Sandstone above Gneudna Formation type section. Note disruption and upwards drag of beds by rising water. Plug of unbedded sandstone occurs in core of volcano.

Yellow, dolomitized carbonate intervals, locally with fenestral fabrics, are present at some levels. Irregular eroded contacts suggest that hardgrounds developed during their deposition.

Distribution and thickness

The Munabia Sandstone outcrops along the eastern margin of the Carnarvon Basin between the Lyndon River and Mount Sandiman Station, a distance of almost 100 km. The sequence is repeated by faulting, forming three belts of outcrop.

The formation thins dramatically to the west, from about 400 m in outcrop to only 31 m in Quail 1. The type section as measured by Thomas and Pritchard (Condon, 1965b) is 555 m thick, somewhat thicker than usual. The thickness of 1311 m near Howell Bore quoted by Condon (1965b) is probably incorrect, as this is a structurally complex area.

Fossils and age

Body and trace fossils are virtually absent. Condon (1965b) reported only lepidodendroid plant remains in the basal beds northwest of Williambury homestead, and similar plant fossils are present in the upper part of the section east of Moogooree homestead. Dwelling structures, resting and moving traces, and burrows occur in the marine brown-sandstone facies. The conodonts *Polygnathus communis* and *Icriodus cornutus* occur in dolomite, in the upper part of the type section, and suggest a Famennian age for the Munabia Sandstone (Nicoll, 1979).

Environment of deposition

Moors (1981a) proposed a braided-fluvial to alluvial-fan depositional model for the Munabia Sandstone and Willaraddie Formation. In this model, proximal alluvial-fan deposits of the Willaraddie Formation grade downslope into braided distal-fan and fluvial deposits of the Munabia Sandstone.

Deposition of the Munabia Sandstone began in a tidal environment, gradational from the underlying Gneudna Formation. Distinctly marine carbonate units (Gneudna lithology) interfinger with thinly bedded, laterally extensive sandstone units (Munabia lithology). Coarsening upward cycles in this transitional sequence suggest beach-bar progradation.

These sediments grade upwards into thick-bedded, multistorey channel-fill sandstone. Channels have scoured bases with little relief which,

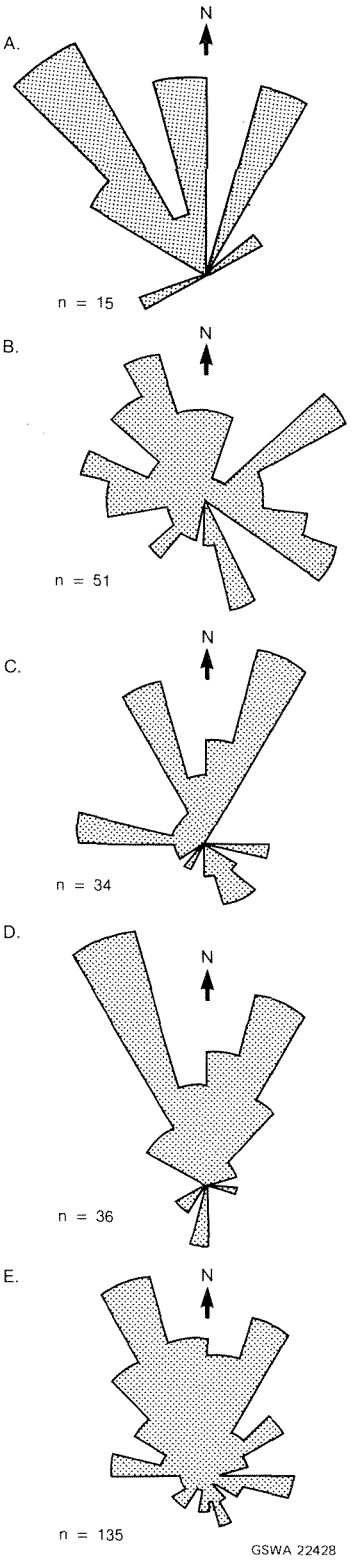

Figure 34. **Palaeocurrent roses for Munabia Sandstone, 20° segments, corrected for tectonic dip. Number of readings — n**

A. Near Moogooree homestead.

B. Near Munaballya Tank.

C. Type section.

D. Yindagindy Syncline.

E. Total for all areas.

Note overall north-northwestwards dominance of readings.

together with the relatively low palaeocurrent scatter, suggest a braided-fluvial environment. The channel-fill sequence fines up and is cyclic. The basal part of a cycle is commonly a massive, coarse to pebbly sandstone, interpreted as a chaotic-lag deposit. This is overlain by planar cross-sets, which were probably deposited within a transverse bar at a high-flood stage. Slumping of these large foresets is due to high water content and high pore pressure brought about by rapid stream flow. The overlying large- to small-scale trough cross-beds were deposited at a falling-water stage within longitudinal bars. The decreasing size of the cross-beds reflects decreasing current velocity (Coleman, 1969). Dominantly flat-bedded sands, in thinner units overlying cross-bedded sands, either result from a further fall in water level or are overbank deposits. The apparent lack of claystone interbeds suggests the former.

Dolomites with conodonts in the upper part of the Munabia Sandstone indicate localized, minor, marine incursions.

Palaeocurrent data show a consistent north-northwest current direction (Fig. 34), with a dominant direction to 337° (vector strength 0.51) and a secondary mode at 022°. The secondary mode may reflect side-bar accretion. These data led Moors (1981a) to suggest a north-northwesterly oriented graben, with a centrally located fluvial system, as a depositional setting for the Munabia Sandstone.

WILLARADDIE FORMATION

Definition

The Willaraddie Formation (Condon, 1954) is a sequence of immature sandstone and conglomerate. In outcrop it conformably overlies the Munabia Sandstone, and is overlain, possibly unconformably, by the Moogooree Limestone. The type section is southeast of Williambury homestead.

Moors (1981a) considered that the Munabia Sandstone and Willaraddie Formation are, at least partly, laterally equivalent. The model he proposed envisaged the Willaraddie Formation as a basin-fringing alluvial-fan sequence which graded downslope into braided-fluvial deposits of the Munabia Sandstone.

Lithology

The Willaraddie Formation outcrops poorly (Fig. 35). In most areas it is masked by a veneer of loose pebbles and cobbles. Immature, poorly sorted, very fine- to coarse-grained lithic wacke is the dominant lithotype, with pebbly sandstone and matrix-supported conglomerate almost as abundant. Cleaner sandstone, grading to quartz wacke and quartz arenite, is less abundant, and claystone intraclasts are locally present.

GSWA 22429

Figure 35. Willaraddie Formation type section, looking south. Note westerly dipping beds near top of hill; generally poor outcrop.

The lithic wacke grades imperceptibly into pebbly sandstone and conglomerate, and all are immature texturally and mineralogically. The quantity of matrix is difficult to establish because of abundant, ductile, lithic fragments, which were probably schist but are now largely indistinguishable from the clay matrix. Grains are poorly sorted and mostly angular to subangular, with low sphericity, Heavy minerals are abundant (Edwards, 1952). Pebbly sandstone and conglomerate are invariably matrix supported, with pebbles making up less than 50% of the rock. All rock types, present as clasts in the conglomerate, are also found as grains in the wacke, indicating a single provenance. Conglomerate clasts are well rounded, and range up to 125 mm in diameter. Resistant siliceous rock-types (grey or black chert, and quartzite) are most abundant, with milky quartz and granitic and schistose clasts less common.

Bedding is poorly developed. Conglomerate beds commonly fine upward into sandstone, but minor coarsening-upward sequences are present locally. Tabular cross-bedding is present in both conglomerate and sandstone, and trough cross-bedding occurs in the sandstone. Tabular cross-bedding generally occurs as isolated, thin (decimetre) sets, while the trough cross-bedding occurs in cosets up to several metres thick with troughs up to 5 m wide and 0.5 m deep. In the conglomerate beds, cross-bedding is commonly outlined only by flat-clast orientation or strings of clasts. Well-developed horizontal stratification is only present locally, in sandstone. Conglomerate beds are usually less than 0.5 m thick, rarely more than 1 m, and commonly have scoured bases with a relief of 10 to 20 cm.

The cleaner sandstone contains less labile components and is better sorted and rounded than the lithic wackes and conglomerates. It occurs in fining-upwards cycles, and is dominantly trough cross-bedded, with horizontal bedding at cycle tops. The depth of the troughs also decreases upwards in the cycles.

Distribution and thickness

The boundary between the Munabia Sandstone and the Willaraddie Formation is gradational, and thus somewhat subjective. Two outcrop belts are present, between Moogooree homestead and the northern end of the Yindagindy Syncline. Outcrops south of Moogooree homestead, which Condon (1962a) showed as Willaraddie Formation, were placed in the Munabia Sandstone by Hocking, Williams, Moore and others (1985) because they could not be differentiated with confidence.

The type section as measured by Thomas and Pritchard (*in* Condon, 1965b) is 294 m thick, and the formation thins southwards. It disappears, or becomes indistinguishable from the Munabia Sandstone, just north of Moogooree homestead. The Willaraddie Formation thickens northwards from the type section but Condon's (1965b) thickness of 1000 m in the synclinal axes is incorrect: the apparent thickness is due to fault repetition and changes in structural orientation.

Because differentiation of the Willaraddie Formation depends on the recognition of alluvial-fan deposits, which in themselves are restricted to basin margins, it is unlikely that the Willaraddie Formation extends far into the Carnarvon Basin. Consequently the correlation of the section in Rough Range 1 between 4127 and 4452 m with the Willaraddie Formation by Condon (1965b) is not accepted here. Following Playford and others (1975, p. 275), this interval is regarded as Gneudna Formation because of its lithology.

Fossils and age

The Willaraddie Formation is largely unfossiliferous, but there was at least one marine incursion similar to those in the Munabia Sandstone, and this introduced the undiagnostic, poorly preserved bryozoans and brachiopods which Condon (1965b) recorded from near the base of the unit, 5 km east-southeast of Williambury homestead.

The Famennian dating of the Munabia Sandstone restricts the age of the Willaraddie Formation to the Late Devonian, possibly extending into the Early Carboniferous.

Environment of deposition

The Willaraddie Formation is an alluvial-fan deposit (Moors, 1981a), rather than a marine deposit as postulated by Condon (1965b). The presence of coarse matrix-supported sandy conglomerate is indicative of deposition by debris flows, rather than by traction currents or from suspension. Sandstone, interbedded with the conglomerate, shows bedforms and grain characteristics typical of a fluvial environment and traction-current deposition. Though the bases of most coarse beds are sharp, there is minimal erosion and the absence of any coarser lag deposit suggests ephemeral sheet floods rather than prolonged channelized deposition. Such conditions occur in the mid-fan region of an alluvial fan where most deposition occurs in lobes surrounding the channels. Interbedded sandstones may be the result of

less catastrophic floods or the more distal equivalent of the sheetfloods, which deposited the conglomerates. Their immature lithology and sorting show their close genetic relationship to the conglomerates.

The clean sandstones in the section are the product of reworking of first-cycle chaotic sediments, either by water moving down the fan (as in a distal-fan environment) or by the reworking of the alluvial fan by a river system.

Palaeocurrent data are sparse, but suggest northwards currents. Locally, secondary modes to the east and west occur. These are best explained by variations in the position of lobes within the fan complex and the expected radial nature of currents.

UNASSIGNED PALAEOZOIC SEDIMENTS

Several separate areas of sedimentary rocks on GERALDTON, east of the Northampton Block, were mapped as Tumblagooda Sandstone by Playford and others (1970). Re-examination of these outcrops suggests that three areas may belong to a post-Tumblagooda Sandstone, pre-Nangetty Formation unit. The areas are immediately north of Bindoo Hill, near Balla wheat bins, and near Nolba.

At Bindoo Hill and near Balla wheat bins, the sediments consist of fine- to medium-grained, poorly to moderately sorted quartz sandstone with minor, scattered, small, angular to well-rounded pebbles. Coarse sand grains are uncommon. Light-green to white clayey siltstone is present in thin interbeds and as intraclasts. Bedding, where visible, is dominantly trough cross-stratification, with lesser horizontal bedding and planar cross-bedding, and palaeocurrents are unimodal to the north. The sorting, bedding structures and palaeocurrent data suggest that these rocks are braided-fluvial deposits.

Although these outcrops are broadly similar to the Tumblagooda Sandstone, there are significant differences. In the proposed depositional model for the Tumblagooda Sandstone the palaeoslope faced northwest, the depositional engergy of fluvial sediments (as expressed by sorting, grain size and pebble content, primarily in FA 1) increased to the southeast, and the amount of marine influence (or abundance of FA 2 sediments) decreased to the southeast. Sediments mapped as Tumblagooda Sandstone along the Northern Gully road, between Indialla Spring and Golaluarra Brook (30 km southwest of Bindoo Hill and 55 km south of Balla wheat bins), consist of very coarse-grained immature pebbly sandstone to cobble conglomerate, which agrees with the model.

The outcrops near Balla wheat bins and Bindoo Hill are inconsistent with the depositional model because they are finer grained and siltier than fluvial intervals of the Tumblagooda Sandstone at the base of the type section, at Pencell Pool, and along the Northern Gully road. This suggests that they may not be Tumblagooda Sandstone. However, their sorting, grain size and gross mineralogy are consistent with them being derived mostly from the Tumblagooda Sandstone.

Near Nolba, between Waggine Spring and the Northampton-Yuna road, fine- to medium-grained, well-sorted quartz sandstone is exposed in a small quarry and a series of north-south ridges. Horizontal bedding, grading into low-angle planar cross-bedding facing to the east, is dominant; with slightly lesser medium- to high-angle, westwards-facing planar cross-bedding with foresets up to 1 m high. Faint trails are present on some bedding surfaces. The sorting and bedforms suggest a beach environment, in which the steeper, west-facing foresets formed on the beach face, and the low-angle to horizontal beds formed on the beach berm to back beach.

No deposits, which could be interpreted as foreshore or backshore beach deposits, are known from the Tumblagooda Sandstone west of the Northampton Block or at Pencell Pool, unlike the outcrops near Nolba. Instead, all marine-influenced deposits are indicative of tidal conditions with a lower nearshore and foreshore palaeoslope than would prevail for beach deposits. Because of this, the outcrops near Nolba are not assigned to the Tumblagooda Sandstone by us. A second reason is that the outcrops are located a significant distance further up the palaeoslope than any other definitely marine-influenced parts of the Tumblagooda Sandstone, reasonably close to possible alluvial-fan sediments (the outcrops along the Northen Gully road).

All three localities are readily related to a single depositional setting, of a braided-fluvial plain sloping down to a moderate- to high-energy coastline fringed by beaches. They may correlate with the interval between 1307 and 1685 m in Wicherina 1, which consists of oxidized fluvial sandstones containing possible Devonian palynomorphs.

CHAPTER 5

Lower Carboniferous

Lower Carboniferous sediments outcrop along the eastern margin of the Carnarvon Basin in the Williambury–Moogooree area, and have been intersected in the subsurface north of 24°S. In outcrop, the sequence consists of the Moogooree Limestone, Williambury Formation and Yindagindy Formation. In the subsurface, the Moogooree Limestone and the Quail Formation have been distinguished. In addition to these units, a Lower Carboniferous sequence, as yet unnamed, is present in the Coolcalalaya Sub-basin (northern Perth Basin).

A unifying feature of the outcrop sequence is the lack of clastic sediments other than in the areally-restricted Williambury Formation, probably because of an arid climate. This is supported by the abundant algal material in the Moogooree Limestone and Yindagindy Formation, and the presence of siliceous nodules with the morphology of evaporitic concretions, which together suggest intermittent hypersaline conditions hostile to grazing organisms. Although substantial hinterland relief must have existed to supply the alluvial fan of the Williambury Formation, both the Moogooree Limestone and Yindagindy Formation are peritidal to shallow-marine deposits throughout the area of outcrop, which extends east-west for about 20 km. This suggests that the basin floor had little topographic relief. Other posible intersections of the Moogooree Limestone in wells also appear to be shallow-marine deposits.

MOOGOOREE LIMESTONE

Definition

The Moogooree Limestone was named by Teichert (1949) and defined by Condon (1954). It is a carbonate sequence containing minimal terrigenous material. The proportion of limestone to dolomite varies from place to place. The unit is overlain conformably by the Williambury Formation, or with apparent conformity by the Yindagindy Formation, and overlies the Willaraddie Formation, probably unconformably. The 326 m thick type section, southeast of Williambury homestead, continues west from the Willaraddie Formation type section.

Lithology

Limestone is the dominant lithology, although dolomite is more abundant than suggested by Condon (1965b). In some areas more than half of the section consists of dolomite beds. Carbonate lithotypes range from mudstone to coarse grainstone. Algal boundstone, which is typically fenestral, is common and shows preferential dolomitization. Sandy carbonate occurs near the top, the base, and at horizons within the formation. Siliciclastic sediments are present, but they outcrop poorly and are less abundant than suggested by Condon.

Mudstone is typically fenestral. The fenestrae outline crude bedding, generally on a decimetre scale but with abrupt domical thickening. These domes, or mounds, are usually roughly hemispherical, up to 2 m in diameter and up to 1 m high. In the most westerly outcrop, west of Harris Bore, they are stromatolitic. Fenestrae have irregular outlines and range in size from an average of 1 cm to less than 1 mm, and are commonly interconnected laterally and vertically. Blocky calcite-spar infill is typical (Fig. 36). Subhedral dolomite crystals adjacent to fenestrae show that dolomitization was early, at least before filling of the fenestrae. Cryptalgal banding is readily recognized in the field.

Of the coarse lithotypes, grainstone is most common, with lesser packstone and rare, lithic-dominated wackestone. Bedding is coarser than in mudstones, and is usually planar and well marked, but at times even abrupt lithological changes (*e.g.* a brachiopod coquina) have no bedding expession. Locally, 20 cm high cross-beds occur, in sets over 0.5 m thick. Shelly debris is uncommon in calcarenites, the bulk of the grains being algal or chemical in origin. Echinoderm fragments are the most widespread fossils, but brachiopods are abundant in some horizons (Condon, 1965b; Lavaring, 1979) and corals occur locally

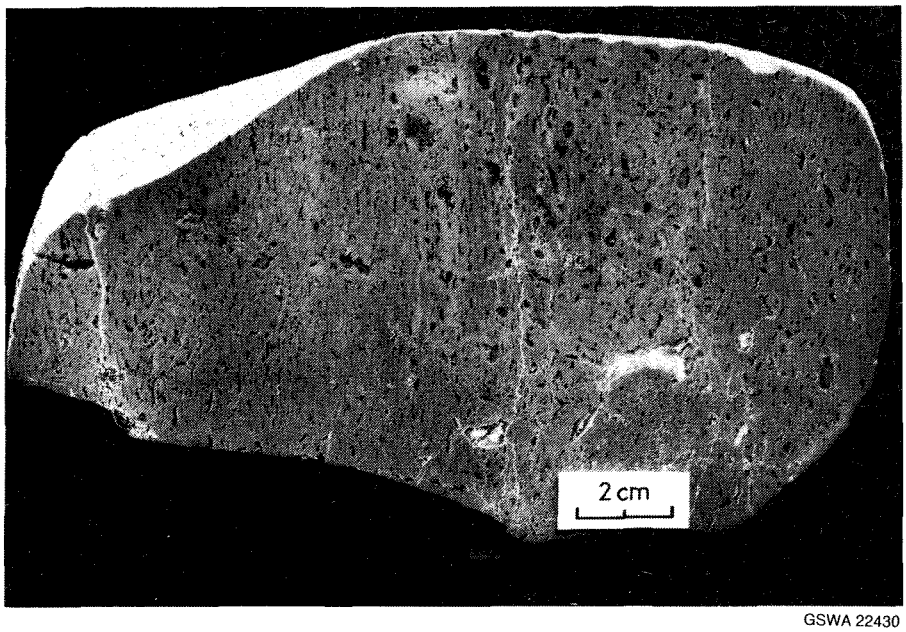

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Figure 36. Polished surface, fenestral lime mudstone of Moogooree Limestone, west of Harris Bore. Fenestrae show excellent lateral continuity with local vertical continuity.

(Lavaring, 1979). Algal remains are virtually ubiquitous and include dasycladaceans and oncolites. Oolites and grapestone are very common in the calcarenites, and oolitic grainstones contain abaout 65% oolites. Clear, blocky, coarse, spar cement generally makes up about 25% of the rock.

Oncolites range in size from many centimetres to less than 1 mm and constitute 30–50% of the rock, the remainder being fractured fragments of oncolites, rare echinoderm-dominated bioclastic fragments, and either sparry cement or post-depositional micritic material.

Quartzose rocks vary from slightly sandy limestone to calcite-cemented sandstone. As quartz grains increase in abundance, so do calcareous lithic grains. Quartz grains are subangular and poorly sorted.

Dedolomitized Moogooree Limestone is well exposed in the ridge east of Moorgooree homestead, where numerous dedolomitized pipes 1 to

GSWA 22431

Figure 37. Closely spaced, circular, dedolomitized pipes of calcite in a dolomitic mudstone, within Moogooree Limestone near Moogooree homestead.

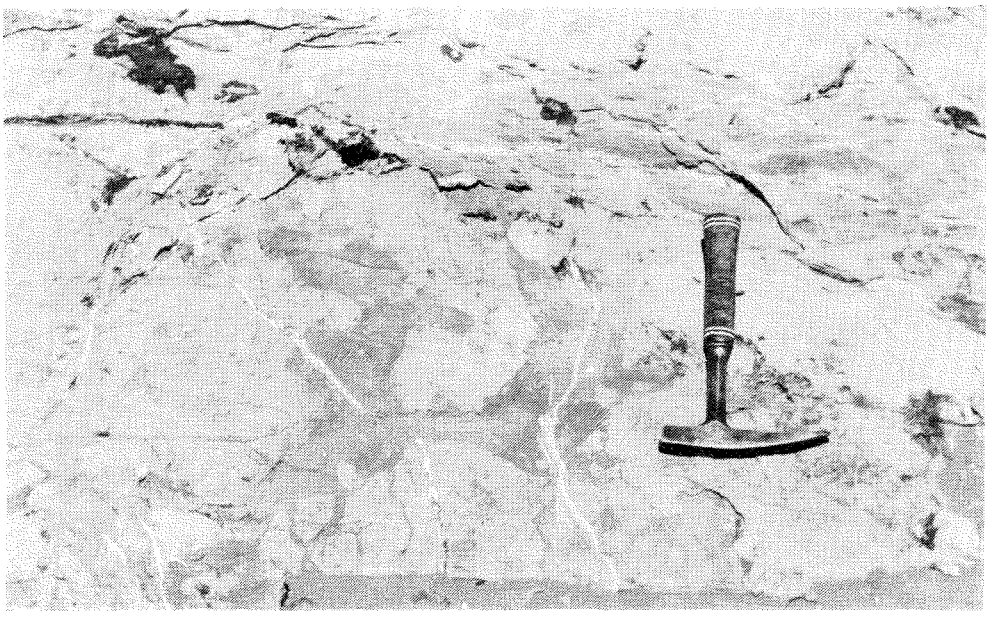

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Figure 38. Dedolomitization zones of fine calcite in Moogooree Limestone, showing "stoping" of dolomitic mudstone. Volumetrically excess calcite crystallizes in fracture.

10 cm in diameter filled with blocky white spar have formed in a dark-coloured, dolomitized, fenestral, lime mudstone (Fig. 37). Concentric fracturing with resorption along the fractures has expanded the pipes. Dedolomitization also occurs along fractures, which progressively widen while preserving the spatial relationships of individual blocks (Fig. 38).

Radke and Nicoll (1981) reported siliceous nodules from the central part of the Moogooree Limestone in the type area. These have the morphology of evaporitic concretions which were later replaced by silica.

Distribution and thickness

The formation outcrops in an almost continuous belt 55 km in length from about 20 km south of Moogooree homestead to 8 km north of Williambury homestead. A 15-20 km long, faulted repetition of the northern part of this belt occurs in the Yindagindy Syncline, 4 km west of Williambury homestead. Isolated outcrops are present further west, about 5 km west of Harris Bore.

Despite the generally bold outcrop, complete sections are rare and thickness measurements are thus subject to considerable error. In the main outcrop belt, the Moogooree Limestone is generally slightly more than 300 m thick (326 m in the type section). South of Moogooree homestead it has been progressively eroded prior to deposition of the Lyons Group. The thickness in the Yindagindy Syncline, where outcrop is very poor, appears to be about 200 m.

In the subsurface, the sequence between 2452 and 2710 m in Quail 1 was correlated with the Moogooree Limestone by Pearson (1964), implying no great change in thickness to the west. In Pendock 1, the interval between 1030 and 1107 m, overlain by Cretaceous sediments, may correlate with the Moogooree Limestone. Condon (1965b) considered that the Moogooree Limestone was present in Rough Range 1 and the Grierson wells, but the sections in question are here considered to be Devonian, following McWhae and others (1958) and Playford and others (1975).

Fossils and age

Algae occur throughout the Moogooree Limestone, and shelly fossils are largely absent. Echinodermal debris is widely distributed, but only disarticulated fragments are found in higher energy deposits. Brachiopod coquinas, as described by Lavaring (1979), are found at discrete horizons and are probably death-assemblages concentrated by major storms. Corals are present in both biofacies, but larger *in situ* forms occur in the *Syringopora* biofacies whereas those in the *Rhipidomella* biofacies are smaller and generally not in growth position.

Based on the brachiopod assemblage, the Moogooree Limestone is Tournaisian (Thomas, 1971).

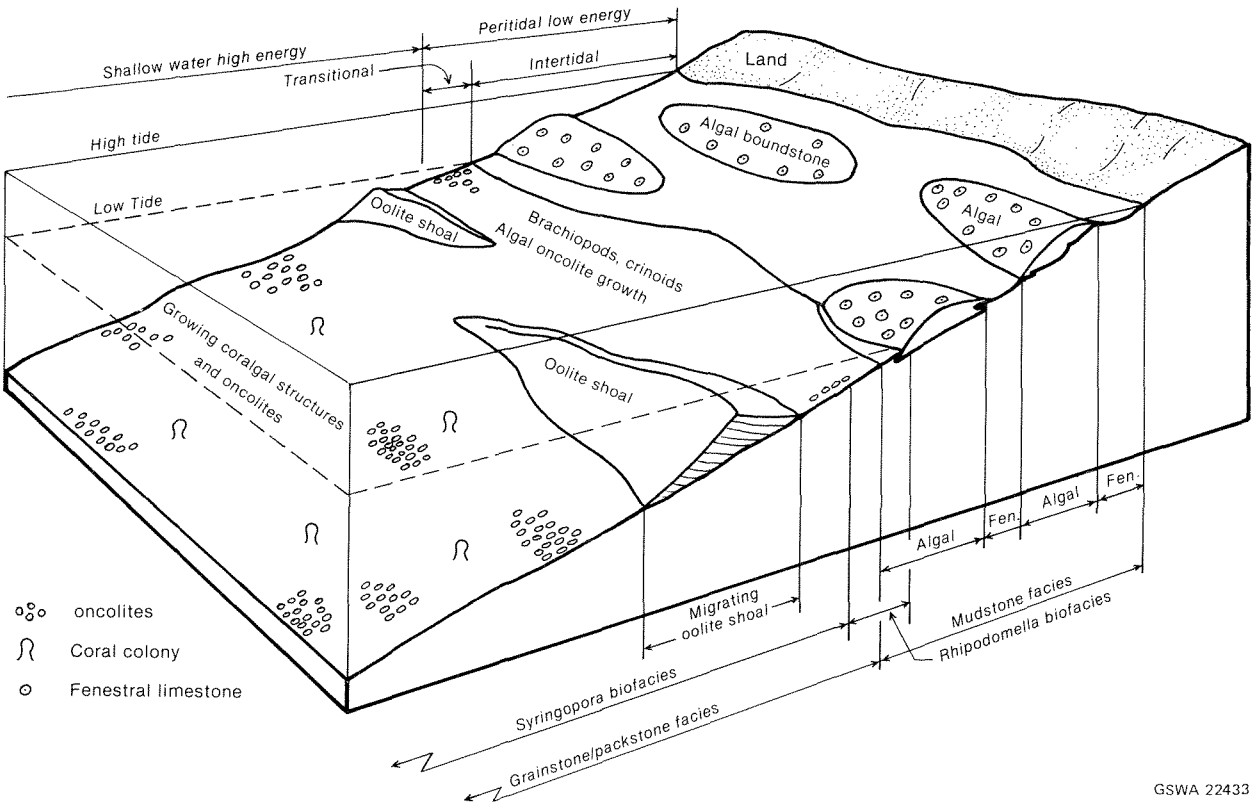

Figure 39. Depositional model for the Moogooree Limestone. Intertidal zone was low energy, and mudstones accumulated, with fenestral or cryptalgal laminated fabric. Sub-tidal zone had moderate- to high-energy conditions and uniformly shallow bathymetry, and grainstones accumulated. Oolitic shoals and oncolite beds migrated along the sea floor, possibly as shoals. Metahaline to hypersaline salinities reduced fauna and flora, with only isolated colonial corals and crinoids in deeper depressions. Allochthonous concentrations of brachiopods accumulated near the strandline.

Environment of deposition

The Moogooree Limestone was deposited in a shallow-marine environment, mostly in peritidal conditions with the remainder in water depths of only a few metres. A gentle eustatic rise in sea level extensively flooded a very flat basin, resulting in only a few laterally persistent, facies. Salinity may have been higher than normal with dolomitization of the sediments as well as the possible deposition of some evaporites. The orientations of 53 elongate spiriferids from two localities suggests that the coastline was oriented north-northwest in the area of outcrop. This is similar to the trend proposed by Lavaring (1979), who interpreted a relatively linear coastline with a gently westwards deepening basin.

Two major depositional environments were present; low energy peritidal and higher energy shallow-subtidal (Fig. 39). The peritidal deposits can be divided into two facies, distinguished by: cryptalgal lamination; and massive bedding with fenestral fabric. Centimetre- to decimetre-scale bedding characterizes both facies and shows pronounced lateral continuity. The two facies are intimately interbedded, although sets of one facies are 2 to 3 m thick in places. An intertidal to shallow-subtidal environment is postulated, with the development of algal mats during periods of low sediment supply and fenestral mudstone (commonly peloidal) when supply was greater. Bottom slopes were probably very gentle and the peritidal area may have been very wide. Minor irregularities were present and occasional banks of broken shells and skeletal algae were concentrated by storms, forming grainstones (if winnowed) or packstones.

The high-energy environment shows currents strong enough to move large fossils and oncolites, but water depth probably did not exceed a few metres. Several facies can be recognized. Lavaring (1979) separated a *Syringopora* biofacies containing corals in growth position, which he regarded as reflecting a stable environment of moderate energy, and a *Rhipidomella* biofacies with transported fossils, indicative of a higher energy environment closer to the strandline.

On lithological grounds two other facies can be recognized in the subtidal deposits: oolitic grainstone and oncolitic grainstone. The oolitic

facies represents an unstable environment in which mobile oolite shoals were free to migrate, while the oncolitic facies represents a more stable environment where local motion was possible but algal growth prevented major migration.

A transgressive-regressive cycle can be seen in most sections of the Moogooree Limestone. For example, in the section east of Moogooree homestead (Fig. 40), the lowest sediments are fenestral and cryptalgal mudstones typical of the peritidal low-energy zone. Accumulation almost balanced the transgression, and a thick zone of similar deposits accumulated. Eventually deeper water conditions prevailed, and coarser grained packstones and grainstones were deposited with the occasional thin (storm deposit) brachiopod coquina. After a short period of such deposition sea level fell again, with algal and fenestral mudstone deposition resuming.

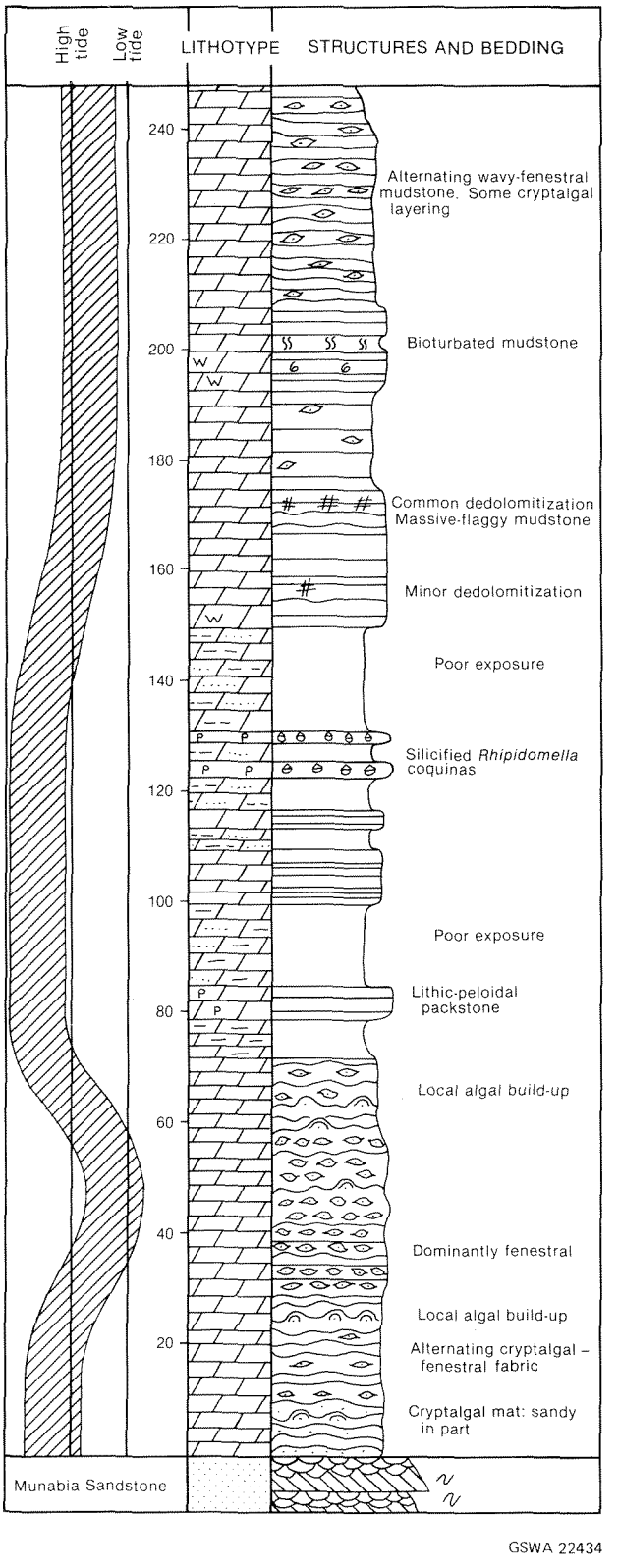

Figure 40. Graphic log of Moogooree Limestone section immediately east of Moogooree homestead. Initial sediments were deposited near low-tide level and built up to, and possibly beyond, high-tide level. Subsidence then increased water depth to shallow sub-tidal until deposition again built up to intertidal.

WILLIAMBURY FORMATION

Definition

The Williambury Formation ("Williambury Sandstone" of Teichert, 1949; amended by Condon, 1954) conformably overlies the Moogooree Limestone and is conformably overlain by the Yindagindy Formation. The type section has a measured thickness of 235 m (Condon, 1965b) and is about 4 km east-southeast of Williambury homestead.

Lithology

The Williambury Formation is very similar to the Willaraddie Formation. Immature sandstone is dominant with significant conglomerate and minor claystone. Because of the poor outcrop, proportions of the different types are difficult to evaluate but Condon (1965b) considered that the type section was 55% sandstone, 30% conglomerate, and 15% siltstone.

Sandstone is texturally and mineralogically immature, falling into the quartz lithic-wacke field. Quartz grains are angular, but lithic grains (dominantly multicoloured cherts) are usually well rounded, implying a multicylic origin. Phyllitic soft grains are abundant and large white mica flakes are locally common. The sandstone ranges from very fine to very coarse, and it grades imperceptibly into grit and conglomerate. Generally, the sandstone is virtually massive, with bedding only vaguely outlined by concentrations of grains or the presence of upward-fining cycles.

Laterally impersistent planar cross-bedding is present locally. Horizontal bedding in finer grained sandstone is, in places, highlighted by mica concentrations on bedding planes. Sandstone intervals range in thickness from decimetres to more than 6 m.

The conglomerate is polymictic, mostly clast-supported, and shows a wide range of thickness and clast abundance. Clasts are well rounded (unless broken during transport) and usually reasonably spherical, though disc- and rod-shaped clasts occur. The largest clasts exceed 15 cm in diameter. Resistant siliceous clasts are most abundant, with less common granitic, gneissic and schistose clasts. Conglomerate intervals commonly fine upwards both by a decrease in grain size and an increase in matrix content, changing from clast-supported conglomerate to matrix-supported conglomerate. They are otherwise mostly massive, with bedding only expressed by clast imbrication. Minor laterally impersistent intervals of horizontal and planar cross-bedding occur.

Claystone occurs in 3 to 5 m thick beds and as flakes in sandstone, but the overall abundance is probably less than the 15% suggested by Condon (1965b). The claystone is almost always silty, and grades from silty claystone to highly argillaceous siltstone. Bedding is generally massive with only a crude lamination in some of the most silty or micaceous zones. Both bleached white and dark reddish-brown claystones are present.

Distribution and thickness

The Williambury Formation occurs in the Williambury and Yindagindy Synclines. Its southernmost extent is about 5 km north of Moogooree homestead. Because of extremely poor outcrop, and the lack of well-developed bedding, it is difficult to measure thicknesses with any degree of accuracy. The thickness for the type section (235 m) and the general picture of a thinning and decrease in maximum clast size to the west and south, given by Condon (1965b), appear to be correct. But other thicknesses, including the maximum of 338 m, could be considerably in error. The Williambury Formation has not been recognized in the subsurface.

Fossils and age

No fossils other than possible plant rootlet impressions have been found in the Williambury Formation. The age therefore is based on the ages of the underlying Moogooree Limestone, which is Tournaisian, and the overlying Yindagindy Formation, which is possibly Visean (Thomas 1971). A Tournaisian age appears most likely.

Environment of deposition

The Williambury Formation is an alluvial-fan deposit similar to the Willaraddie Formation, but was deposited much higher on the fan. At least one deep, conglomerate-filled channel, typical of the proximal-fan environment (Heward, 1978), is present in the type section. Similarly, the conglomerates show a much higher proportion of clasts to matrix, suggesting that the source of supply was closer. The lack of definite bedding also indicates the less-organized regime of water-deficient debris flow (Reading, 1978).

The thick claystone intervals in the Williambury Formation were probably deposited in a topographically low interlobe area occupied by a lake or swamp. A swamp environment is more probable as some of the claystone contains possible plant rootlets and subaerial soil horizons.

Variations in thickness of the Williambury Formation suggest that the apex of the fan was northeast of Williambury homestead.

YINDAGINDY FORMATION

Definition

The Yindagindy Formation ("Yindagindy Limestone" of Teichert, 1950; amended and defined by Condon, 1954) is a sequence of interbedded sandstone and limestone, conformable on the Williambury Formation and unconformable beneath later sediments. The base is the lowest hard limestone bed, and the top (where preserved) is generally a ferruginized interval reflecting the unconformity with the Lyons Group. The type section is immediately north of the old road to Williambury, 4 km west of the homestead in the Yindagindy syncline.

Lithology

Outcrop of the Yindagindy Formation is poor and calcareous lithotypes are the only rock visible, unless the terrain has substantial relief. Detailed measured sections are thus impossible to obtain (see Read and others 1973, Fig. 2, for examples) and proportions of lithologies must be estimated. Generally, limestone makes up about 20% of the Yindagindy Formation although at some localities such as near Moogooree homestead, up to a third of the unit is limestone (Read and others 1973, Fig. 2).

The dominant lithotype in the Yindagindy Formation is quartzose sandstone. Compositionally it is very similar to the

Williambury Formation, with abundant lithic grains. Various cherts are common as well as crystalline acid rocks and scattered feldspar. Limestone grains are abundant in the upper Yindagindy Formation, reflecting carbonate deposition in the basin. Sorting is better than in sandstone from the Williambury Formation, reflecting additional transport and winnowing. Another significant difference is that the sandstone has characteristically thin horizontal bedding. Cross-bedding is rare and restricted to thin sets of planar foresets. Because of the poor outcrop, it is not possible to determine whether regular vertical sequences or cycles are present.

The limestone is predominantly a fine-grained calcilutite, with lesser packstone, grainstone and some brachiopod coquinas. It is characterized by the presence of algal-derived material ranging from cryptalgal filaments to stromatolites. Except in the coquinas, almost all fossils have an algal rim. Siliciclastic grains are common, and locally are sufficiently abundant to form a calcareous sandstone. Oolites, grapestones, and oolites with a grapestone core are also common on some horizons. Most oolitic rocks are grainstones with no micritic matrix, indicating efficient winnowing by currents.

Some of the carbonate has been dolomitized, usually into a fine-grained mosaic but sometimes into a coarser (almost euhedral) mosaic of crystals. The coarser dolomitization may be due to a later process, but the fine-grained lithology must represent contemporaneous dolomitization as chips are frequently included in unaltered limestone.

Fenestral fabric, though not abundant, occurs commonly in both grainstone and mudstone. Generally, fenestrae are small and scattered. Bioturbation is also present. As described by Read and others (1973) subvertical tubes, up to 1 cm in diameter and filled with coarse spar, are related to burrowing into sediment which had already attained some cohesion. However, most of the bioturbation was syndepositional.

Distribution and thickness

The Yindagindy Formation extends from just south of Moogooree homestead to the northern end of the Yindagindy Syncline. Further south, it was completely eroded prior to the deposition of the overlying Lyons Group. Read and others (1973) divided the Yindagindy Formation in the Moogooree homestead area into four units, which they could correlate within this small area. However, these may only have local significance as the section appears to become sandier, overlying the Williambury Formation alluvial fan, and other clastic sources may similarly have local overprint.

The thickness of the Yindagindy Formation is highly variable because of erosion by the Lyons Group. The type section is 76 m thick, and the maximum thickness noted by Condon (1965b) is 116 m, at the south end of the Yindagindy Syncline.

Fossils and age

Coquinas occur and many of the limestones contain complete individual fossils, but the fossils are difficult to extract from the matrix and the fauna has not been studied in detail. Forms identifiable in thin section (*e.g.* corals) have unfortunately not been found in outcrop. Algae, both calcareous and non-calcareous, and gastropods are very common. The brachiopod coquinas contain rhynchonellids, athyrids, and spiriferids (Condon, 1965b). Other fossils which have been found include ostracods (*Cryptophyllus*) crinoids and possibly foraminifers, which Read and others (1973) identified bryozoans and serpulids, and Condon (1965b) listed a nautiloid.

On the basis of the brachiopods, Thomas (1971) suggested a possible Visean age.

Environment of deposition

The presence of interbedded immature sandstone and marine carbonate indicates a shallow-marine basin backed by a high hinterland from which large volumes of terrigenous sediment were derived. The poor exposure of the sandstone renders detailed environmental interpretation impossible, so in the following section, emphasis is placed on the carbonate intervals.

Carbonate grain size and texture suggest that water energy ranged from high to low, with ooid and quartz sand forming beaches or mobile shoals in shallow water. Fine-grained sediments accumulated in quiet backwaters behind shoals or in a peritidal environment (suggested by fenestral fabric).

The sparsity of fossils may be either a reflection of a salinity variance or a turbid water environment. Though a wide range of fossil groups including gastropods is present, the widespread occurrence of algae indicate that browsing animals were not so abundant as to pose a threat. The only times when fossils are abundant are in localized, storm-concentrated coquina layers.

Adjacent to sediment fans entering the sea (near Williambury homestead), the main rock type is sandstone, with subordinate carbonate. Away from these sediment sources (near Moogooree homestead), the proportion of limestone increases (Read and others, 1973). This trend probably continued further south and west where no outcrop of the formation is present.

QUAIL FORMATION

Definition

The name Quail Formation has been used in internal reports by WAPET geologists since the drilling of Quail 1, where it was first recognized (Pearson, 1964). The name was published, but not defined, by Johnstone and others (1976) and formalized by Hocking (1985). The Quail Formation is the sequence of interbedded siltstone, sandstone and claystone, which overlies Lower Carboniferous sediments (Moogooree Limestone in Quail 1) and is overlain by glacigene sediments of the Lyons Group. The section in Quail 1 between 2100 and 2452 m (Fig. 41) is the type section. Other sections of the Quail Formation are in Rough Range 1 (2809–3260 m), Warroora 1 (1509–1826 m, total depth), Gnaraloo 1 (450–502 m, total depth) and Minderoo 1 (387–610 m, total depth). A Lower Carboniferous section was encountered in Cane River 1 (Hematite Petroleum, 1972a, b), but the lithology differs from other sections of the Quail Formation, rendering correlation uncertain.

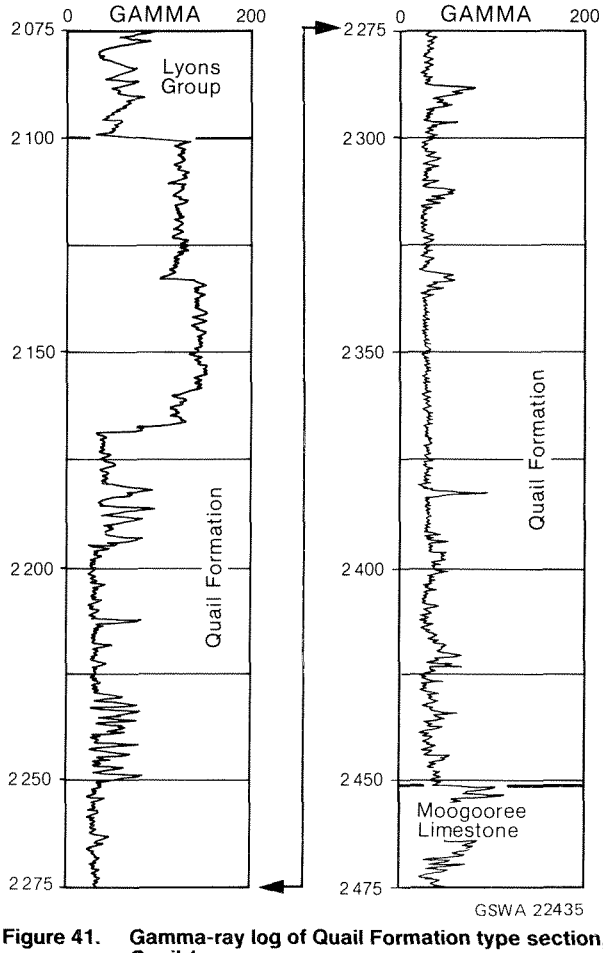

Figure 41. Gamma-ray log of Quail Formation type section, Quail 1.

The Quail Formation correlates partially or fully with the Williambury and Yindagindy Formations of the eastern Merlinleigh Sub-basin. The top of the Quail Formation may be younger than the Yindagindy Formation.

Lithology

The Quail Formation consists of an upper silty sequence overlying a lower thicker sandy sequence. The unit fines westward and northward from Quail 1. The lower sequence in Quail 1 is a relatively uniform sandstone, whereas significant interbedded fine-grained sediment is present in Warroora 1, Minderoo 1, and Rough Range 1. In Waroona 1, the gamma-ray log suggests a coarsening-upward cycle overlain by two major fining-upward cycles, but in Minderoo 1 this is replaced by relatively massive sandstone overlain by a coarsening-upward cycle. Several fining-upward and coarsening-upward cycles are present in Rough Range 1.

Sandstone in the Quail Formation is mostly grey, fine- to medium-grained lithic wacke to quartz wacke, with scattered coarse grains and rare pebbles. It is commonly silicified or dolomitized, with negligible porosity. The fine-grained sediments are medium- to dark-grey siltstone to shale. The calcareous content of both the sandstone and the fine-grained sediments is variable. In Quail 1 two thin limestones are present near the base of the sequence (Pearson, 1964), while in Minderoo 1 beds of very fine-grained argillaceous limestone are present in the upper, shaly part of the sequence (Johnstone and others, 1963). Pearson (1964) suggested that the limestones in Quail 1 may correlate with the Yindagindy Formation.

Distribution and thickness

The Quail Formation is only known from the deeper parts of the central Carnarvon Basin which were not subject to erosion prior to deposition of the Lyons Group. The formation is 352 m thick in Quail 1 and 451 m thick in Rough Range 1; these are the only two complete sections. It is greater than 317 m thick in Warroora 1, greater than

223 m in Minderoo 1 and greater than 52 m thick in Gnaraloo 1. To the north, the correlation with the sequences in Cane River 1 (414–694 m) and Cane River 2 (347–413 m) is uncertain, and the Quail Formation is absent in East Marrilla 1, where Lyons Group rests on Moogooree Limestone (Osborne, 1972).

The unit probably does not extend much further south than Gnaraloo 1 and Quail 1, if the correlation with the outcropping Lower Carboniferous to the east is correct. This is because the Lyons Group progressively oversteps older Carboniferous and Devonian units, south of about 24°S; and the Quail Formation, being the uppermost unit in this sequence, would be the first to be removed.

Fossils and age

The Quail Formation is only sparsely fossiliferous. Spores and pollen from the Quail Formation were listed by Johnstone and Pudovskis (1955), Balme (*in* Pearson, 1964) and Edgell (*in* Johnstone and others, 1963). Wood fragments are also present in the formation in Quail 1. Palynomorphs in Quail 1 suggest that it is of Early Carboniferous age (Balme, pers. comm., 1981). This is supported by comparison of the assemblage in Minderoo 1 (Edgell, *in* Johnstone and others, 1963) with that found in the Anderson Formation of the Canning Basin and also in Cane River 1 (Balme, *in* Hematite Petroleum, 1972a).

Environment of deposition

Because of the limited amount of data, the depositional setting of the Quail Formation is uncertain. The lower, sandy unit is probably a marine-shelf to shoreface deposit, and the fine-grained upper unit is probably a low-energy marine-shelf deposit. Wave and current action was not strong, as the sandstone is generally not well winnowed. Sand bodies within dominantly fine-grained parts of the Quail Formation are probably sand bars and shoals which migrated laterally over the shelf. Changes within the environment were mostly gradual rather than abrupt, because of the dominance of fining-upward or coarsening-upward transitions rather than sharp changes

A marine-shelf setting is preferred to a tidal setting (which on lithological grounds is equally plausible) because facies are reasonably persistent laterally, a feature which would be less likely in a tidal setting.

UNNAMED LOWER CARBONIFEROUS SEDIMENTS

Exploratory drilling for coal in the Coolcalalaya Sub-basin of the northern Perth Basin in 1981 indicated the presence of a Lower Carboniferous clastic sequence in the area extending south from Lake Nerramyne to the Greenough River (North Broken Hill Ltd, 1982). The sequence consists of more than 116 m of grey and red-brown claystone (in part sandy and pebbly) and locally containing minor limestone concretions and fossils. Palynological study of the sequence indicated an Early Carboniferous age (Balme, *in* North Broken Hill Ltd, 1981; Balme, *in* North Broken Hill, 1982).

Similar sediments also occur between Corktree Well and Wongong Well on Muggon Station. They outcrop in the east-facing scarp in this area and were mapped by van de Graaff and others (1983) mostly as High Cliff Sandstone because of stratigraphic relationships apparent at Pats Dam, a short distance to the north. The sediments consist of siltstone, mudstone (in part pebbly) and cobble conglomerate. From drill-hole data, the thickness of the sequence is more than 95 m (Samantha Exploration N.L. and others, 1981). Balme (*in* Samantha Exploration N.L. and others, 1981) suggested an Early Carboniferous age for the sequence, but did not exclude the possibility that it could be Devonian.

The sequence has not been named here because of the lack of knowledge concerning it. Outcrops of Palaeozoic sediments between Muggon and Lake Nerramyne are indistinctive for the most part, and some of them could be Lower Carboniferous. Similar sediments are also present, but undated, at other localities east of the Northampton Block on GERALDTON, (*e.g.* Barraweelbarra Hill) and a systematic study of the entire area is needed before a new stratigraphic unit is defined. The sequence is dissimilar to the unassigned sandstone exposed at Bindoo Hill and Nolba, and intersected in Wicherina 1 (McTavish, 1964). It represents another post-Silurian, pre-Late Carboniferous unit.

Possible dropstones and varvoid bedding near Barraweelbarra Hill suggest part of the sequence is glacigene, but without further study it is not possible to suggest a depositional environment for the unit as a whole.

However, this sequence together with the Bindoo Hill/Nolba sequence indicate the presence of a moderately sized depositional basin in the northern Perth Basin/southern Carnarvon Basin in the Early Carboniferous and ?Devonian.

CHAPTER 6

Upper Carboniferous-Upper Permian

The Upper Carboniferous–Lower Permian sequence of the Carnarvon Basin can be divided into two major depositional phases, which are unconformity-bounded in onshore areas. The first of these consists of the Lyons Group and Callytharra Formation, and spans the period of the late Carboniferous (Stephanian) to Late Sakmarian. The second consists of the Wooramel, Byro and Kennedy Groups, and spans the period of the Middle Artinskian (Baigendzhinian) to Late Artinskian (Roadian) or Kazanian.

The first phase is characterized by glacial influence on sedimentation. It has not been established precisely when deposition of the lower unit (the Lyons Group) began: the Stephanian age is derived from dating of basal Lyons Group beds in East Marrilla 1 (Osborne, 1972). The Lyons Group, as now defined, includes the Harris Sandstone and Carrandibby Formation, and contains mixed siliciclastic and carbonate lithologies. It was deposited during a major continental glaciation, within which several glacial maxima and minima occurred. The uppermost formation of the group, the Carrandibby Formation, reflects the melting of the ice sheet, and is transitional into the Callytharra Formation. The overlying Callytharra Formation is a highly fossiliferous siltstone and calcarenite deposited during post-glacial, eustatic sea-level rise.

The second phase of deposition is characterized by siliciclastic fluvial, deltaic and marine-shelf deposition. It is separated from the first phase by a major unconformity spanning all or part of the Aktastinian (Early Artinskian), which is expressed east of Gascoyne Junction as a karst terrain on the underlying limestone, and further north near the Lyndon River as a faunal break. Deposition began in a transgressive episode with major terrigenous influx superimposed, producing the laterally variable and (locally) complexly interrelated fluvial, deltaic and shallow-marine sediments of the Wooramel Group. Terrigenous input lessened, and deposition continued in storm-dominated marine environments, with periodic subsidence of the basin, forming the Byro Group. The basin stabilized, and the Kennedy Group was deposited, forming a broad marine shelf. Choking of the basin may have occurred in the later stages of deposition. It is not known when deposition finished, because age-diagnostic fossils have not been found in the upper two thirds of the Kennedy Group.

Near Kennedy Range, the thickness of the Late Carboniferous–Early Permian sequence is approximately 4300 m. No well has penetrated a complete Permian sequence, but the total thickness may exceed 5000 m.

LYONS GROUP

Definition

The Lyons Group ("Lyons Conglomerate" of Maitland, 1912; "Lyons Series" of Raggatt, 1936; Lyons Group of Teichert, 1950; "Lyons Formation" of van de Graaff and others, 1977; reinstated by Hocking, 1985) is a mixed siliciclastic sequence with lesser carbonate, which is unified by a pronounced glacial influence on sedimentation. It was described in some detail by van de Graaff (1981). The type section, north of the Wyndham River on GLENBURGH, is poorly exposed, faulted and does not intersect the top or base of the group.

Condon (1962a) named, as formations within the group, the Austin Formation, Coyango Greywacke, Dumbardo Siltstone, Koomberan Greywacke, Mundarie Siltstone, Thambrong Formation and Weedarra Shale. However, these units cannot be reliably recognized away from their type areas and are invalid in the sense in which Condon (1962a, 1962b, 1965a, 1967) used them. Therefore, they are not considered further here, because of their lack of usefulness and limited validity. The Harris Sandstone and Carrandibby Formation (both of which show the characteristic glacial influence) are the only named units in the Lyons Group. The Harris Sandstone includes the "Austin Member" as mapped by Williams, Williams, Chin and others (1983), Williams, Williams, and Hocking (1983), Hocking, Williams, Moore, and others (1983), and Hocking, Williams, Lavering and Moore (1983). The Lyons Group thus has a

discontinuous named formation at the base and a relatively continuous named formation at the top, but the bulk of the group is not subdivided. It was reinstated as a group because further work on this undivided section could distinguish formations. We anticipate that these would be areally restricted, and that there would be a far greater number of formations than the seven which Condon (1962a) proposed. The formations comprising the group in one area could well be totally different to those in another area.

Lithology

The Lyons Group is poorly exposed, with outcrops restricted to isolated cuestas, mesas, low ridges, and creek sections. It underlies gently undulating plains of pebbles, cobbles and boulders, which are residual lag-concentrates of framework clasts from which the matrix has been winnowed. Many clasts show plucking, striations and/or facetting. Van de Graaff (1981) noted that pebbles have concentrations of several hundred per square metre (estimated from slabs of tillitic material), cobbles and small boulders between several to some tens per square metre, and metre-sized boulders, several per hundred square metre (estimated from field photographs). Boulders of greater than 2 m diameter are known from many localities but are not common. The largest known boulder (originally more than 4 m diameter) is near South Branch Bore, on the north bank of the Minilya River.

Significant concentrations of larger than average boulders form boulder beds. The lag concentrates to which the term "boulder bed" generally applies are up to 10 m across and can be traced for several hundred metres on the ground (Fig. 42), and for several kilometres on air photographs. Different boulder beds vary considerably in composition, reflecting different source terrains. They represent major depositional events, but with the absence of detailed studies it is not clear just how great a lateral extent individual boulder beds have, or how many are present in the Lyons Group.

The conglomerate of the Lyons Group is best described as a diamictite. The matrix locally consists of poorly to moderately sorted sandstone, siltstone, claystone, shale or limestone, all of which are variably calcareous and in places contain marine fossils. Both unbedded massive diamictites and bedded diamictites occur, with the size of the boulders commonly greatly exceeding bed thickness. The rock types present as clasts show a wide variety (van de Graaff, 1981). They include various granites (most abundant), quartzite, quartz, sandstone and siltstone, metamorphic rocks, chert and carbonates, and pegmatite and basalt (least abundant). The crystalline, feldspar-rich rock types are usually only seen in fresh exposures since they are rapidly destroyed by weathering, leading to a false impression that resistant rock types are most abundant. Clasts of underlying Phanerozoic sediments such as the Gneudna Formation are rare.

GSWA 22436

Figure 42. Boulder bed in Lyons Group near Deathtrap outcamp, Bidgemia. Shrubs in foreground are about 50 cm high. Note concentrations of larger boulders in bed, also cobble and pebble lag over landscape.

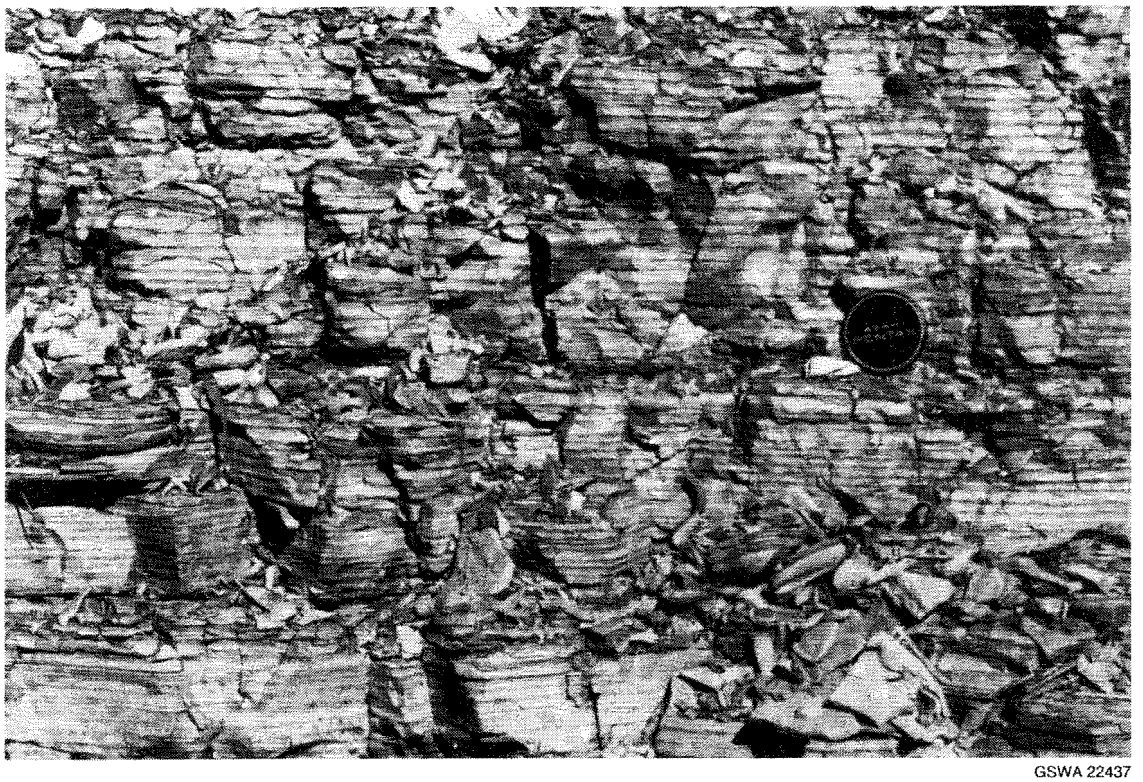

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Figure 43. Varves in Lyons Formation, Coordewandy homestead. Darker units are finer grained than light-coloured silt-sized units. Lens cap is 53 mm in diameter.

In addition to the basal Harris Sandstone, there are significant amounts of sandstone in the Lyons Group, as discrete lenticular intervals of feldspathic and lithic arenite and wacke. Bedding within sandstone intervals varies from small to medium scale, with trough and planar cross-stratification and, in finer parts, ripple lamination. Fine-grained ripple-laminated and small-scale cross-bedded calcareous sandstone and quartzose calcarenite also occur, most commonly in the upper part of the group.

GSWA 22438

Figure 44. Inversely graded chaotic-mudflow deposit in Lyons Group near Durrabiddy Well, Dairy Creek. Note variety of rock types, sandstone drape over uppermost boulders. Rock presumably accumulated by breaching of a moraine wall by dammed water.

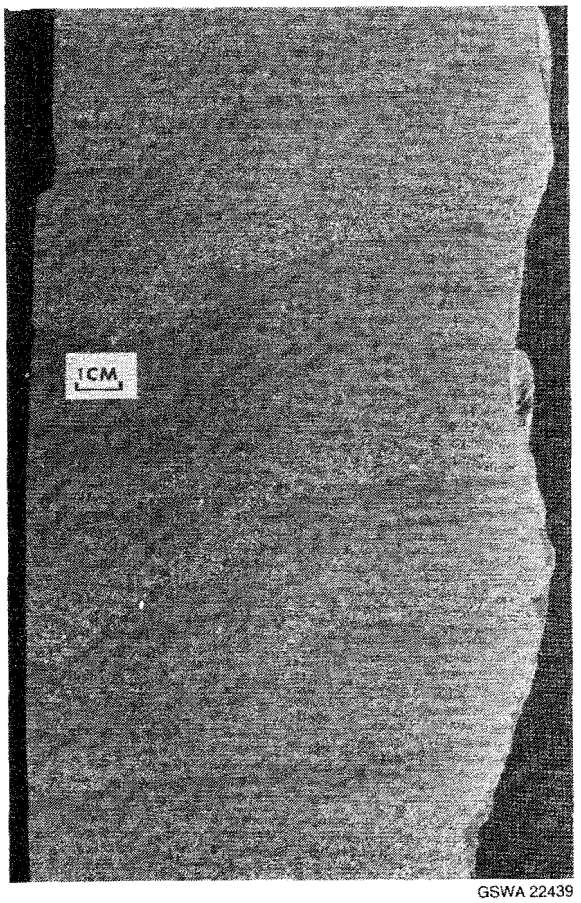

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Figure 45. ***Graded bedding*** **and syndepositional microfaulting in Harris Sandstone, north end of Weedarra Inlier. Sediment was deposited from suspension in glacial lake adjacent to outwash delta, and underwent slumping and microfaulting before any lithification. Grain flow of coarse sand is clear in centre of specimen.**

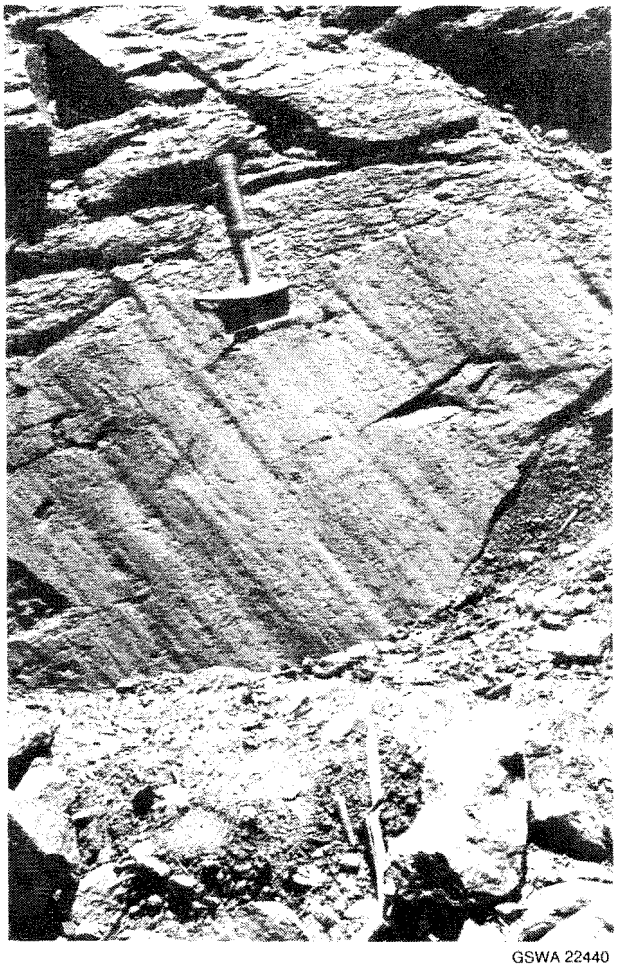

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Figure 46. Basal pavement cut in Precambrian gneiss, northwest side of Weedarra Inlier. Pavement is overlain by cross-laminated siltstone, fine sandstone and a boulder bed.

Laminated, commonly contorted, siltstone occurs throughout the group. Varves are known from several localities (Condon, 1967). Approximately 34 m of varved siltstone, shale and fine sandstone, in couplets 1 to 15 cm thick are present at Coordewandy homestead (Fig. 43), and about 10 m of varved sandstone are present east of Congo Pool at the southern nose of the Congo Syncline.

Other lithological features noted during mapping include contorted bedding, syndepositional small-scale faulting, soft-sediment ice-drag straie (restricted to the Harris Sandstone except 4 km southeast of Mount Sandiman shearing sheds), with inverse and normal grading of sediments ranging from fine-grained sandstone to boulder conglomerate (Figs 44, 45, 46, 47).

Distribution and thickness

The Lyons Group is exposed throughout the Merlinleigh, Byro and Bidgemia Sub-basins in an outcrop belt some 430 km long and up to about 70 km wide. The Nangetty Formation and Holmwood Shale of the Perth Basin are correlatives of the main glacigene portion of the group and the Carrandibby Formation, respectively. In the subsurface, the Lyons Group is present north of 25°S in the Gascoyne Sub-basin and on the Peedamullah Shelf. It is absent in the southern Gascoyne Sub-basin, presumably because of post-Permian erosion.

The greatest known thickness of the Lyons Group is in Remarkable Hill 1, between 896 m and 3206 m (total depth). Berven (1969) did not place the lowermost 850 m, which is probably Carboniferous but still appears to be glacial in origin, in the Lyons Group. Hocking and others (1980) included this interval in the Lyons Group, agreeing with Kemp and others (1977) who placed the lower part of the Lyons Group (and equivalent units) in the Canning and Perth Basins in the Upper Carboniferous. The only subsurface section with a stratigraphic top and base is in Quail 1 between 592 and 2100 m (a thickness of 1508 m).

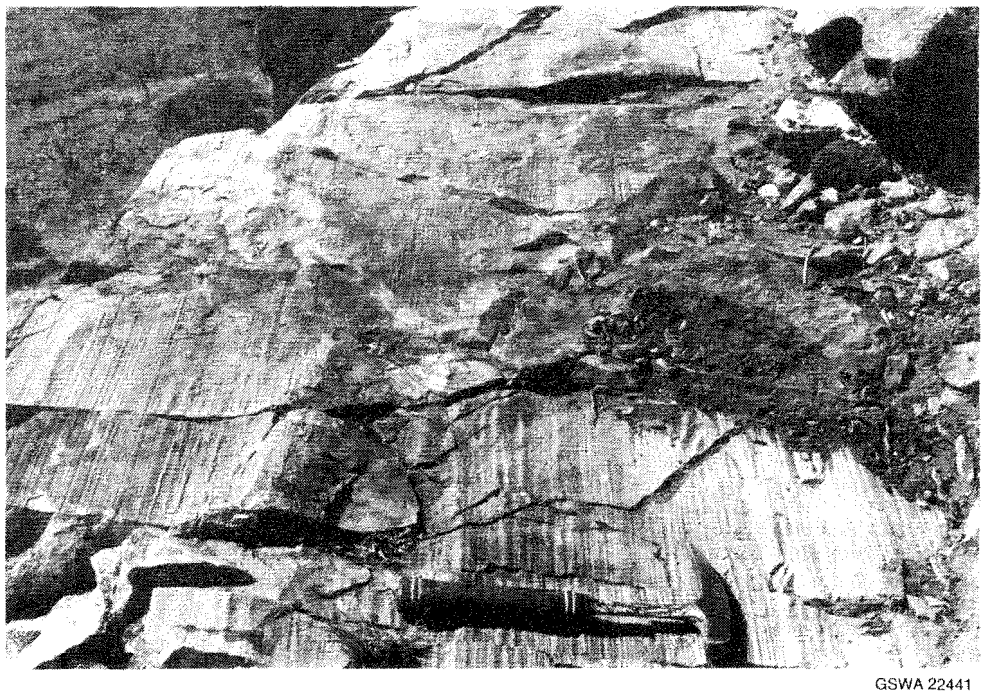

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Figure 47. Soft-sediment ice-drag striae in Harris Sandstone east of Alison Well. Note preservation of fine detail and expanse of striated surface. Pavement is underlain by approximately 20 m of sandstone and tillite.

Significant incomplete sections have been intersected in Warroora 1 (1165 m), Rough Range 1 (911 m) and Onslow 1 (290 m).

The thicknesses cited by Condon (1954, 1967) and Konecki and others (1958) for the Lyons Group, in outcrop, are unreliable. Faulting, the extent of which was not fully realized by previous workers, is common within the Permian sequence and casts doubts on measurements of thick, poorly exposed sequences like the Lyons Group. However, it is clear that the thickness of the group is quite variable. Immediately south of the Carrandibby Inlier for example, it is only about 32 m thick (Konecki and others, 1958), whereas only 20 km to the northeast, in BMR 8 (Mount Madeline) it is greater than 365 m thick (Mercer, 1967).

Fossils and age

The fauna of the Lyons Group consists of bivalves, gastropods, brachiopods, crinoids, bryozoans and foraminifers, and has been described by Dickins and Thomas (1959) and Dickins (1956, 1957, 1963). Lycopod plant fossils and plant microfossils are also present. Dickins (1978) placed the fauna in a climatic context, noting that it has a low diversity because of the cold conditions during deposition.

The age of the Lyons Group as determined from this fauna is Sakmarian, or Asselian using the time scale of Harland and others (1982) as done by Dickins (1985, Fig 2). However, in Remarkable Hill 1, Late Carboniferous palynomorph assemblages are present in the lower 850 m of the Group (van de Graaff, 1981), and in East Marrilla 1 the lowermost Lyons Group was intersected and dated as Late Carboniferous (Osborne, 1972). The beds can probably be assigned to Unit I of Kemp and others (1977), which is here considered to be Late Carboniferous, with Unit II the lowermost Permian. This indicates that the Lyons Group spans the Permian-Carboniferous boundary, at least in deeper parts of the basin. The lower boundary of the unit is undoubtedly diachronous, with deposition commencing earlier in deeper, more central parts of the basin. A Late Carboniferous age has yet to be confirmed from outcrop, as the plant remains in the Harris Sandstone are not sufficiently age-diagnostic (A. E. Cockbain, pers. comm., 1981). The position of East Marrilla 1, relative to outcropping Lyons Group and the basin margin, suggests that in the central Merlinleigh Sub-basin the base of the Lyons Group may be Carboniferous. In the Byro and Bidgemia Sub-basins, the group may be entirely Early Permian in age.

Environments of deposition

The Lyons Group is mainly a glacio-marine deposit, with lesser glacio-lacustrine and fluvio-glacial sediments. Glacigene conditions are indicated by poorly sorted to unsorted diamictites, striated and facetted clasts, striated surfaces,

varves, the variety of clast types, and low faunal diversity. Both marine and continental (glacially influenced), environments can be distinguished.

Massive, unbedded tillites probably formed beneath continental and grounded marine ice-sheets, whereas bedded tillites formed beneath ice-shelves in marine and, locally, ?lacustrine conditions (van de Graaff, 1981). No unequivocal examples of dropstones, with deflected bedding, have been found. But this is not surprising considering the poor exposure of the Lyons Group and the poorly bedded nature of the tillites. The areal extent of glacigene deposits and the interfingering of marine and terrestrial deposits indicate that deposition took place on a wide marine shelf with an adjoining coastal plain. Clasts within tillites are commonly well rounded, indicating a period of transport by supraglacial, englacial or proglacial streams as well as transport by ice.

Condon (1967) suggested that contorted bedding within the Lyons Group, was produced by icebergs pushing unconsolidated sediments. However, there is no overthrusting in the sediments as could be expected in ice-pushed deposits (Flint, 1971, p. 122), and no subglacial striae have been found within or immediately overlying contorted deposits. Instead, we consider that contorted intervals (such as are present at Alison Well on KENNEDY RANGE or immediately north of No. 22 Well on GLENBURGH) formed either by the collapse of ice-contact deposits after the supporting ice melted, as van de Graaff (1981) suggested, or by the disruption of originally well-bedded sediments in a glacio-lacustrine dammed basin. The dam wall could either melt (if composed of ice, as suggested by Jackson and van de Graaff, 1981, for similar rocks in the Officer Basin), or simply burst (if composed of sediment under pressure from greater meltwater input).

Glacio-lacustrine environments are indicated by varves, as at Coordewandy homestead. These have been found only in the Byro and Bidgemia Sub-basins, which suggests that lacustrine conditions may have been confined to eastern, basin-margin areas.

Sandstones in the Lyons Group which do not show significant indications of glacial influence (this includes much of the Harris Sandstone) were deposited mainly in fluvial environments. This is based primarily on the unimodal palaeocurrent pattern shown by sandstones, the poor to moderate sorting, and the locally common silty interbeds. The relatively low scatter of palaeocurrent directions further suggests deposition in a low sinuosity, braided-fluvial setting. The bedding types, grain size and lack of observed cyclicity correspond best to the Platte-type braided-fluvial profile in Miall's (1978) classification. Braided streams such as these are common on fluvio-glacial outwash plains (Edwards, 1978). Proglacial alluvial-fan deposits have not been specifically recognized, but may be present in the Arthur River outcamp area and east of Coordewandy homestead, where some apparently non-tillitic conglomerates are patchily exposed.

The varied assemblage of rock types which occurs as erratics in the Lyons Group indicates a very large source area. Grey and others (1977) identified stromatolite erratics which were carried some hundreds of kilometres from localities in the north to northeast. Banded iron-formation erratics have been found which were also derived from a northerly to northeasterly direction. Of the glacial pavements known from the base of the Lyons Group (Fig. 46), two have north-south striae (Grey and others, 1977). All these features suggest a hinterland source area ranging from the Gascoyne Province to the Pilbara Block, with southwards to westwards transport of material, rather than a glacial centre to the south or southeast as suggested by Crowell and Frakes (1971). The erratics, of course, reflect only the ultimate provenance: there were probably intermediate stages of transport before incorporation in the Lyons Group.

The orientation of striae in the striated surfaces found within the Lyons Group is varied (Fig. 48), and reflects local rather than regional ice-movement directions. Cross-bed orientations are also varied, but in general range from westwards to northwards, as with most Palaeozoic sandy clastic deposits in the Carnarvon Basin. These palaeocurrent directions indicate that while the main glacial centre may have been located in the north to northeast, significant sediment input took place from the east, with ice as well as streams flowing westwards into the basin.

Pronounced glacial influence persisted for about 20 million years, during which time more than 120 000 km^3 of dominantly glacigene sediments were deposited in the Carnarvon Basin. This indicates a far greater glacial imprint than was recognised by Crowell and Frakes (1971). Five glacial intervals, separated by four interglacial intervals, were interpreted by Condon (1954). Dickins (1985) agreed with this, on the basis that glacial phases were unsorted, and interglacial phases showed sorting in sediments. It is clear that the Lyons Group shows the effects of several successive glaciations, rather than one prolonged

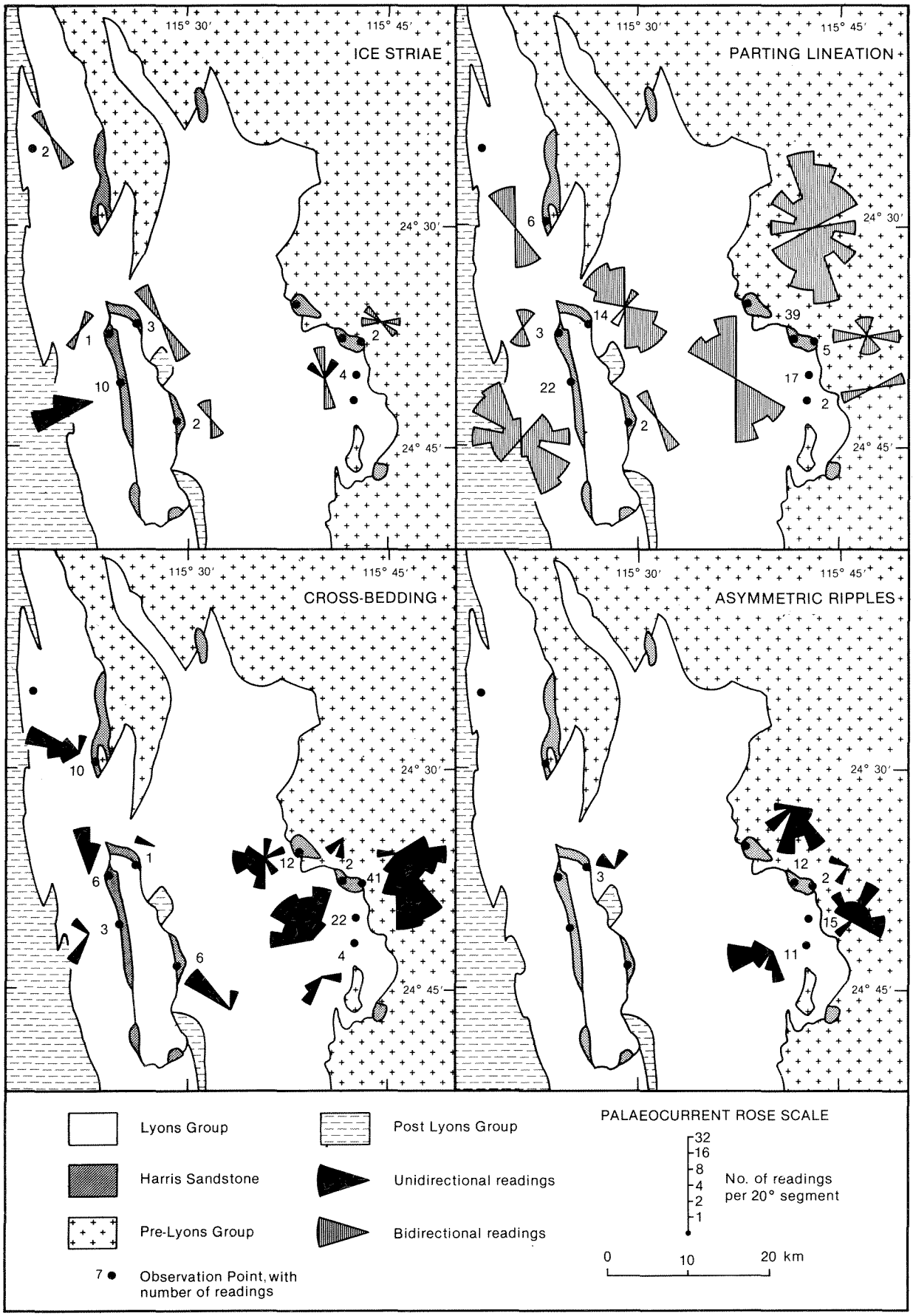

Figure 48. Palaeocurrents and ice-striae orientation in the Lyons Group, eastern Merlinleigh and Bidgemia Sub-basins. Note general northwest trend of current indicators except on west side of Weedarra Inlier.

glaciation. However, we consider that the number of glaciations, their relative severity, and their effects, remain uncertain.

HARRIS SANDSTONE

Definition

The Harris Sandstone (Condon, 1954) was included within the "Lyons Formation" by Hocking, Williams, Lavaring and Moore (1983) after evidence of glacial influence in the unit was found near the type section. The "Austin Member" of the "Lyons Formation" was included in the Harris Sandstone by Hocking (1985) because the distinction between the two units is subtle and does not merit the retention of both names for units which are stratigraphically equivalent. "Harris Sandstone" has priority over "Austin Formation" or "Austin Member".

The Harris Standstone is a discontinuous basal unit within the Lyons Group, dominated by sandstone. Resistant quartzose and feldspathic to lithic sandstone characterizes the unit, and it is mapped only where this lithofacies is present at the base of the Lyons Group. Boulder beds and siltstone which are locally interbedded with the sandstone (as at Mount Sandiman homestead) are included within the Harris Sandstone. Where this situation occurs, the upper boundary of the unit is placed at the top of the uppermost of these sandstone intervals. Above this level, there are generally major thicknesses of tillitic siltstone (boulder beds) and, locally, thin feldspathic sandstone. It is recognized that, by this definition, the stratigraphic level of the top of the Harris Sandstone varies from locality to locality. But defined as such, the unit is readily mappable and it groups together distinctive sandstone facies at the base of the Lyons Group.

The Harris Sandstone overlies the Yindagindy or Williambury Formations in the Williambury-Moogooree area, but south of Moogooree homestead it progressively oversteps older rocks until it rests on Precambrian basement at Mount Sandiman and the Weedarra Inlier. Read and others (1973) considered the sandstone to be conformable on the Yindagindy Formation near Moogooree, but in this area the topmost 10 m of the Yindagindy Formation appear to be leached of calcareous material and patchily ferruginized. We consider this to indicate subaerial weathering of the Yindagindy Formation before deposition of the Harris Sandstone. This, combined with the evidence of glacial influence in the Harris Sandstone (particularly in its type area) indicate that the Harris Sandstone is unconformable on the Yindagindy Formation as well as older units.

Lithology

Two slightly different sandy lithofacies characterize the Harris Sandstone. The first corresponds to the traditionally recognized Harris Sandstone in the Yindagindy Syncline, and the second to what was previously called the Austin Formation or Austin Member. Commonly, both are silicified, and form resistant ridges.

The first lithofacies consists of moderately to well-sorted, medium- to coarse-grained quartz arenite, with minor quartz wacke, siltstone and pebble conglomerate. Bedding varies from even, horizontal bedding to trough and planar cross-bedding, with foresets generally between 30 cm and 1 m high. Current ripples are locally present on topsets, as is primary current lineation. Minor siltstone and silty sandstone is locally interbedded, in units up to 1.5 m thick.

The second facies is similar to the first, except that the sandstone is only poorly to moderately sorted, with uncommon well-sorted intervals. Clay drapes are common on rippled surfaces, and siltstone is locally significant. The sandstone is feldspathic arenite and wacke as well as quartz arenite and wacke.

Beneath the main sandstone interval, east of Alison Well (Lyons River) and at the north end of the Weedarra Inlier, boulder beds with a silty matrix are present immediately overlying Precambrian basement. These coarsen upwards into fine silty sandstone, thin-bedded and cross-laminated, which in turn coarsen upwards into resistant quartz and feldspathic arenite. East of Alison Well, the sandstone interval consists of fining-upward sequences from pebble conglomerate to sandstone, occasionally with silty interbeds. The sequences are confined to channels approximately 10 m wide and 2 to 3 m deep.

Ice-drag striae within sandstone are known from six localities, and are abundant east of Alison Well (Figs. 47, 49) and west of Deep Well (both on Lyons River Station). These striae are best preserved on clay-draped surfaces, and directions of ice movement can be inferred from pushed pebbles, truncated ripples and grain imbrication. The sandstones were deposited in distributary channels of an outwash delta, prograding into a lake or sea. Ice moved over these deposits, and grounded while the sand was unconsolidated or semiconsolidated. Such striae have been reported

GSWA 22443

Figure 49. Detail of striated surface east of Alison Well. Direction of movement of ice (to right) can readily be determined in stereo, as small "foreset" is present in centre of photograph. (Turn page sideways for stereo).

from ancient sequences in Antarctica (Lindsay, 1970), India (Banerjee, 1966) and South America (Frakes and Crowell, 1969), and a similar origin was proposed to that outlined above.

Graded beds (1–8 cm thick) with syndepositional faulting (Fig. 45) are present at the north end of the Weedarra Inlier, 20 km east-northeast of Lyons River homestead. These formed as suspension deposits from turbid flows entering glacial lakes.

Discrete ridges and hills of cross-bedded sandstone, with foresets at least 7 m high, occur in the Arthur River outcamp area; an excellent example is located immediately northeast of Salt Well. The hills rest on Precambrian basement, and are either surrounded by basement or grade laterally into tillitic siltstone. They formed in glacial-outwash deltas, and support the interpretation made of the graded beds and ice-drag striae.

Distribution and thickness

The Harris Sandstone occurs discontinuously at the base of the Lyons Group between the Williambury area and Coordewandy. It is generally less than 50 m thick, and commonly only a few metres thick. The type section in the Yindagindy Syncline is 85 m thick, and the greatest measured thickness is 332 m at Mount Sandiman homestead, which includes several interbedded boulder beds. This latter section is the "type section" of the "Austin Formation" (Condon, 1967), with the upper 46 m above the last resistant sandstone interval omitted.

The unit outcrops as discontinuous lenses or pods, in a pattern which appears to have been determined partly depositionally and partly by underlying topography. The sandstone facies changes laterally to an interbedded sandstone/siltstone facies in a prominent mesa immediately south of Corktree Well (Eudamullah). But a few kilometres south (south and southwest of Arthur River outcamp, on the south side of Cream Creek) the distribution of the sandstone is clearly controlled by basement topography, with ridges of Precambrian rocks several tens of metres high forming a rugged pre-depositional landsurface.

To the west, the Harris Sandstone has not been identified in the subsurface.

Fossils and age

The age of Harris Sandstone is poorly established. The only fossils known are impressions of lepidodendroid plants. These range from small twigs to relatively large branches which at one locality have some pinnules attached (Fig. 50). White (1959) identified one specimen as *Lycopodiopsis pedroanus* and inferred a probable Early Permian age for it. White and Condon

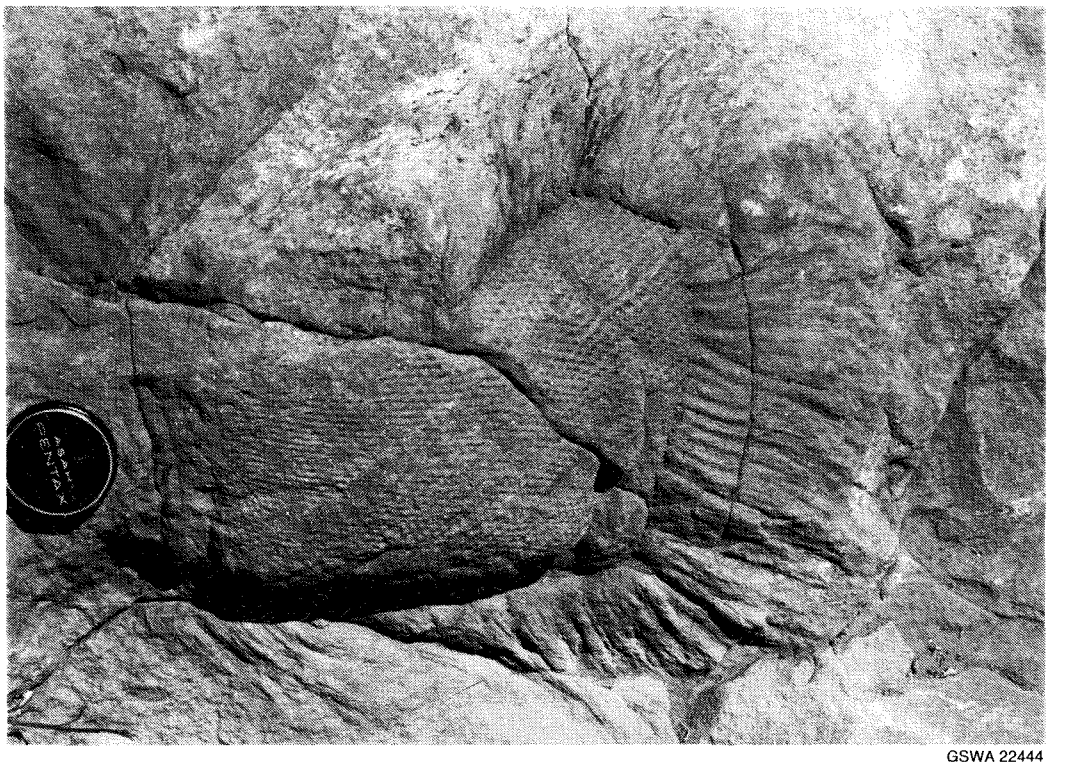

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Figure 50. Lepidodendroid trunk with pinnules attached, from Harris Sandstone immediately above Yindagindy Formation type section. Lens cap 53 mm diameter.

(1959) and White (1959) described other specimens from sandstones in the basal Lyons Group, which are now included in the Harris Sandstone — but it was stated that they could be of Permian or Carboniferous ages. No further work has been done on these lepidodendroid remains.

Since then, a Late Carboniferous age has been established for the base of the Lyons Group in East Marrilla 1 (Osborne, 1972) and in Remarkable Hill 1. Both wells are further into the basin than the outcrop areas of the Harris Sandstone, and the base of the Lyons Group is undoubtedly time-transgressive, but to what extent is unknown. Therefore, in the absence of further palynological data, it cannot be stated whether the Harris Sandstone is of Late Carboniferous or Early Permian age.

Environments of deposition

Two related environments of deposition can be distinguished for the Harris Sandstone. At the onset of glaciation, some areas were emergent whilst others were covered by lakes or seas. In emergent areas, the Harris Sandstone was deposited as fluvial outwash, or sandur, deposits. The relief on the landsurface may not have been great where it was composed of Devonian and Carboniferous sediments (as for example in the Yindagindy Syncline), but where Precambrian basement was exposed, the topography was locally rugged, and deposition was areally restricted. The emergent areas graded laterally and downslope into lakes and seas, where the Harris Sandstone formed as glacial-outwash deltas, prograding into (locally) relatively deep water. Evidence for this environment is as follows: the large-scale cross-bedding near Salt Well, Eudamullah; the glacial striae within the sandstone; the graded bedding at the north end of the Weedarra Inlier; the underlying boulder beds at several localities; and sandstone lenses surrounded by boulder beds as at Mount Sandiman homestead.

There is little evidence in the form of onshore-directed cross-stratification to suggest significant wave reworking of sandstones, which indicates that well-sorted sandstones were produced by current winnowing rather than wave winnowing.

CARRANDIBBY FORMATION

Definition

The Carrandibby Formation was defined by Konecki, Condon, Dickens and Quinlan (*in* McWhae and others, 1958) as the unit lying, with apparent conformity, on the Lyons Group and overlain conformably by the Callytharra Formation. Dickens and Thomas (1959, p. 65) considered the Carrandibby Formation to be part of

the Lyons Group, because of common palaeontological, lithological, and "lithogenetic" features. Condon (1967, p. 57) considered that the formation was unconformable on the Lyons Group, because of the sharp lithological change between the two units near Callytharra Spring and the apparent truncation of the "formations" of the Lyons Group beneath the Carrandibby Formation. We consider that these "formations" are not lithostratigraphic or chronostratigraphic units, but indicate that the Lyons Group was deposited in part as large prograding wedges, which the Carrandibby formation "blanketed", in a return to a layer-cake depositional style.

In the present study, the Carrandibby Formation is considered to be a transitional unit at the top of the Lyons Group. The lithology of the formation is generally similar to the fine-grained facies of the lower part of the Callytharra Formation, but locally contains scattered glacial erratics, indicating some glacial influence. It can thus be regarded as part of the same glacially dominated phase of sedimentation as the Lyons Group. For this reason, the Carrandibby Formation is included within the Lyons Group as the uppermost named formation.

The type section of the Carrandibby Formation is at the south end of the Carrindibby Inlier, 1 to 2 km west of Callytharra Spring, and is 59 m thick. The maximum known thickness is 72 m, in BMR 8 (Mercer, 1967). The formation is not recognized in the subsurface outside the Byro Sub-basin.

Lithology

The Carrandibby Formation has a variable lithology, and commonly resembles the immediately overlying Callytharra Formation. Adjacent to the Carrandibby Inlier, the Carrandibby Formation is composed dominantly of soft shale and siltstone which is dark grey to greyish green in fresh exposures. The formation both coarsens and becomes more calcareous upwards, with increasing amounts of calcilutite and calcareous siltstone. Near the top of the unit, there are significant intercalations of fine-grained quartz and feldspathic wacke.

In the Merlinleigh Sub-basin, a calcareous mudstone containing numerous fragmented fossils and scattered quartz sand and glacially derived material, ranging from granule to cobble size (Fig. 51), is here interpreted as Carrandibby Formation. This unit is virtually identical with the fine-grained facies of the lower part of the Callytharra Formation except for the presence of glacially derived material, which appears to have been deposited from suspension. The material indicates that the unit is a separate facies, transitional between the Lyons Group and the Callytharra Formation.

Distribution and thickness

Condon (1967) recognized the Carrindibby Formation only in the central and southern Byro Sub-basin, where he cites thickness as ranging from 10 m, near the junction of Bilung Creek and

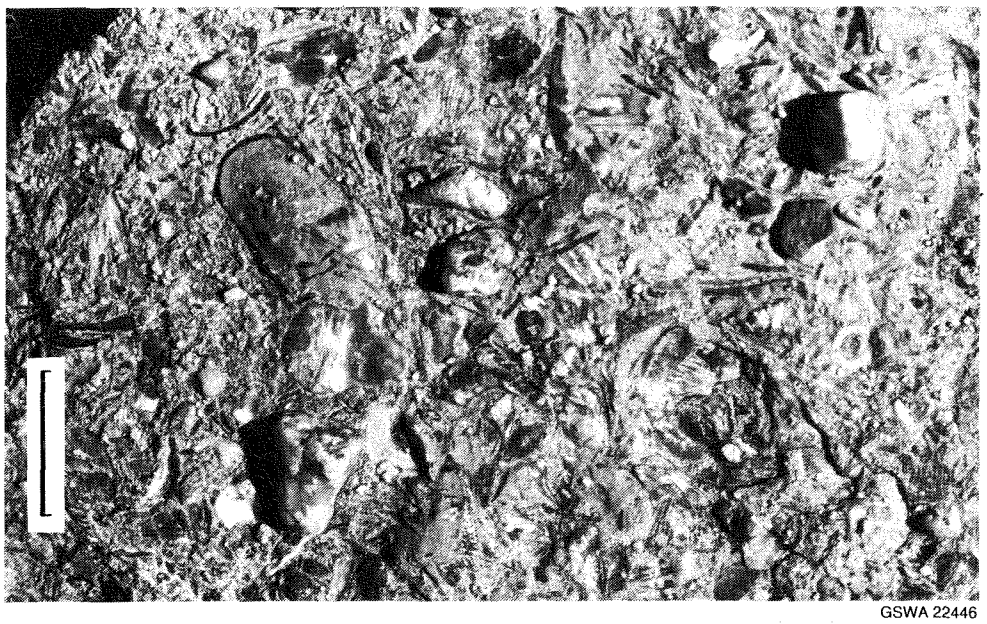

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Figure 51. Fossiliferous limestone with small dropstones and pebbles of glacial origin from Lyons Group (Carrandibby Formation equivalent), Mia Mia Station. Note granitic pebbles. Larger dropstones also occur in this facies. Scale bar is 2 cm.

the Wooramel River, to 59 m in the type section, with 72 m in BMR 8 (Mount Madeline) and 36 m in BMR 9 (Daurie Creek). Williams, Williams, and Hocking (1983) extended the unit to a poorly exposed kaolinized siltstone and fine-grained sandstone in the proper stratigraphic position west of Coordewandy homestead.

In the Merlinleigh Sub-basin, the distinctive transitional facies between the uppermost Lyons Group and Callytharra Formation is the stratigraphic equivalent of the Carrandibby Formation, and was assigned to it by Hocking, Williams, Moore and others (1983), Hocking, Williams, Lavaring and Moore (1983), and Denman and others (1983). The southernmost locality where it is recognized is on the eastern side of Pells Range, west of Fletchers Well (Dairy Creek), and it has been recognized as far north as the Pleiades Tank (Mia Mia) area. It is less than 10 m thick, and is commonly absent or only 1 to 2 m thick. For this reason it is not shown on WINNING POOL-MINILYA or KENNEDY RANGE.

The Carrandibby Formation has not been recognized in the subsurface outside the Byro Sub-basin, probably because of the difficulty of distinguishing it from either the Lyons Group or the Callytharra Formation. The unit correlates with the Holmwood Shale of the Perth Basin. This is a much thicker unit, of the order of 450 m (Playford and others, 1976), indicating that the depocentre in the late Sakmarian lay south of the Carvarvon Basin.

Fossils and age

The Carrandibby Formation contains a marine fauna which is generally regarded as being of Sakmarian age (Dickins, 1963, 1978). Dickins (1978) placed the Carrandibby Formation in Stage A of his (1963, 1969) subdivision of the Western Australian Permian, and Dickins (1985, Fig. 2) showed the unit as Tastubian (early Sakmarian). The fauna has a low diversity (Dickins, 1978) and was described by Dickins and Thomas (1959) and Dickins (1957, 1963).

Environment of deposition

The Carrandibby Formation was deposited in a low-energy, offshore-marine environment. The low diversity of the fauna indicates cold conditions with normal oceanic salinities, rather than a restricted basin (Dickins, 1978). This is supported by the scattered glacial erratics, indicating the presence of icebergs which calved from the remnants of the continental ice-sheet. The upwards increase in carbonate in the Carrandibby Formation reflects changes in calcium carbonate solubility, as the frigid conditions (associated with the main phase of glaciation) ameliorated slightly. The upwards increase in sand content is probably due largely to increased surface runoff in the hinterland of the basin, as the climate ameliorated.

UNGROUPED UNIT

CALLYTHARRA FORMATION

Definition

The Callytharra Formation (Condon, 1954; "Callytharra Limestone Group" of Dee and Rudd, 1932; "Callytharra Stage" of Condit, Raggatt and Rudd, 1936; and Raggatt, 1936) is a sequence of interbedded fossiliferous siltstone, calcilutite, and calcarenite, which conformably overlies the Lyons Group and is disconformably overlain by the Wooramel Group. The type section is on the south bank of the Wooramel River 1 km west of Callytharra Spring, from which the name is derived. Condon (1954) established a reference section on the south bank of the Lyndon River near Round Hill Well.

Lithology

Two broad facies can be distinguished over most of the area of outcrop of the Callytharra Formation. A fine-grained facies dominates the lower part of the Callytharra Formation, and a calcarenite facies dominates the upper part. The calcarenite facies is poorly developed in the type section on the Wooramel River and in the main reference section on the Lyndon River.

The fine-grained facies (Figs 52, 53) consists of fossiliferous greyish-green calcareous siltstone, locally a calcisiltite. It is commonly soft and friable, and it contains variable amounts of quartz sand. Bedding varies from thinly laminated to blocky. Smaller macrofossils such as bryozoans are mostly fragmented. Thin interbeds of the calcarenite facies are interspersed throughout the fine-grained facies, and increase upwards in thickness and abundance.

The calcarenite facies (dominant in Fig. 54) consists of fossiliferous, yellow to greenish grey, variably quartzose calcarenite. It is resistant to weathering and forms cuestas. Friable calcarenite and siltstone are interspersed throughout the facies. Fossils are mostly fragmented. Bedding is

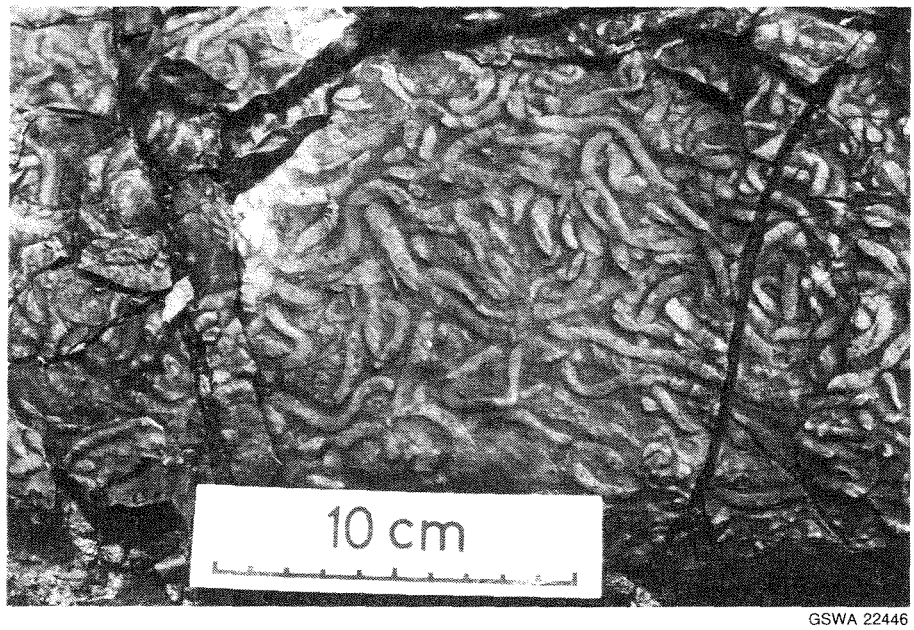

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Figure 52. ***Intensely burrowed calcareous mudstone from lower Callytharra Formation, west of Coondoo outcamp. Typical of low-energy facies.***

generally tabular, and individual beds range in thickness from about 10 to 40 cm. Flat armoured surfaces, consisting of a lag concentrate of medium to coarse-grained quartz sand, cap some beds. Labyrinth karst, with towers up to 30 m high, is developed on this facies over a large area.

Laminated limestone is present in the calcarenite facies at numerous localities, particularly in the area between the Minilya River and the north end of Kennedy Range. However, the layering is of diagenetic origin, as it follows joints and transgresses bedding planes.

The calcarenite facies may be confined to areas reasonably close to the basin margin. It has not been recognized in the subsurface, where the Callytharra Formation is mostly dark-grey to black calcareous siltstone, grading to shale. The formation is more calcareous in the lower part, with thin limestone beds in the lower 56 m in Quail 1 and a limestone interval in the lowermost 43 m in Remarkable Hill 1. In Kennedy Range 1, reasonably close to the area of outcrop, there is no clear development of the calcarenite facies, which suggests that the facies only developed in relatively shallow waters near the basin margin.

GSWA 22447

Figure 53. **Bioclastic packstone showing wide variety of fossils and well-preserved delicate forms. From central part of Callytharra Formation type section. Match shown for scale.**

Distribution and thickness

The Callytharra Formation is exposed in the Merlinleigh and Byro Sub-basins, between the Lyndon and Wooramel Rivers. A small outcrop of the calcarenite facies is present in Pats Dam on Muggon Station, but was shown as Holmwood Shale by van de Graaff and others (1983). The outcrop is overlain by High Cliff Sandstone (Moogooloo Sandstone), not Pindilya Formation as stated by Condon (1967, p. 69). He also stated that the Callytharra Formation was present in Coolyun Well, Byro Station, but it was not found by us.

In the Gascoyne Sub-basin, the Callytharra Formation occurs only in Giralia 1 and Remarkable Hill 1; elsewhere it has been removed by erosion. In Onslow 1, the overlying Wooramel Group is present, but the Callytharra Formation is absent, probably because of early Artinskian erosion rather than non-deposition.

The thickness of the Callytharra Formation in outcrop varies markedly, as shown by Condon (1967). The reference section near the Lyndon River in the Merlinleigh Sub-basin is the thickest outcropping section, at 244 m. Further to the northwest, sections in Giralia 1 and Remarkable Hill 1 are of comparable thickness, at 265 and 201 m, respectively. The former is the thickest known intersection.

From the reference section, the Callytharra Formation thins to the southeast, with a thickness of about 160 m in the Middalya–Mount Sandiman area, and 70 to 80 m in the Bidgemia Sub-basin. Near Pells Range, Bidgemia 1 penetrated 90 m of Callytharra Formation without reaching the base (Condon, *in* Koluzs, 1972). This suggests that the figure of 24 m given by Condon (1967) for this section 7, not far to the east, in unduly low. Additionally, the thickness shown by Condon (1967) for his section 2, Bush Creek, is less than the deposited thickness because of faulting. In the Wooramel River area, the formation thickens to the southwest, from 61 m in Bilung Creek through 81 m in BMR 9 (Mercer, 1967) to 101 m in the type section.

The Callytharra Formation thus thins towards the eastern basin margin and towards the Pells Range–Dairy Creek area. The thinning coincides with the development of the upper, calcarenite facies and the area of the karst terrain.

Karst features on the Callytharra Formation

A labyrinth (or tower and corridor) karst terrain formed on the Callytharra Formation prior to deposition of the overlying Wooramel Group. The presence of the karst has implications for the deposition of the upper part of the formation, and is therefore discussed here. The karst has been recognized in an area of more than 1000 km^2, between Coonantha Well (Bidgemia), Red Ochre Well (Dairy Creek) and the southern end of Pells Range, and may be present in the Monument Syncline and north of Coonantha Well. Although previously interpreted as sea stacks by Condon (1967), among others, old field notebooks show that J.R.H. McWhae recognized the karst as such in the early 1950s.

The karst formed on hard calcarenite of the Callytharra Formation and, where exhumed, distinct karst towers and corridors can be seen (Figs 54, 55). It is very well exposed at: 24°54′S, 115°27′E; 25°08′S, 115°35′E and 25°20′S, 115°42′E. The corridors are up to 20 m wide and follow intersecting sets of master joints. Tower height is mostly between 3 and 8 m, although pinnacle-shaped towers up to 30 m high are exposed at 25°06′S, 115°35′E.

The karst is covered by Moogooloo Sandstone which, in the karstified area, is generally a fine- to medium-grained sandstone, with rare marine trace fossils. Synclines are present within the sandstone infills in some karst corridors. These may be compaction features due to continued solution of limestone under a sand cover, which could also explain the lack of coarse limestone debris within the corridors.

Brook and Ford (1978) proposed the term labyrinth karst for similar karst which they recognized as having formed in climates ranging from humid-tropical to arctic, rather than the specific humid-tropical climate traditionally associated with karst development. Thus the presence of karst on the Callytharra Formation need not indicate a tropical interlude between cold periods, indicated by the glacigene Lyons Group and glacial erratics in the overlying Wooramel Group. However, Wopfner (1978, 1981) postulated a warm "spike" in the latest Sakmarian in South Australia, which suggests that the karst on the Callytharra Formation may have formed in warm rather than cold conditions.

Fossils and age

The Callytharra Formation is one of the most fossiliferous units in the Carnarvon Basin, both in the abundance of fossils and the variety of species. The fauna includes brachiopods, gastropods, bi-

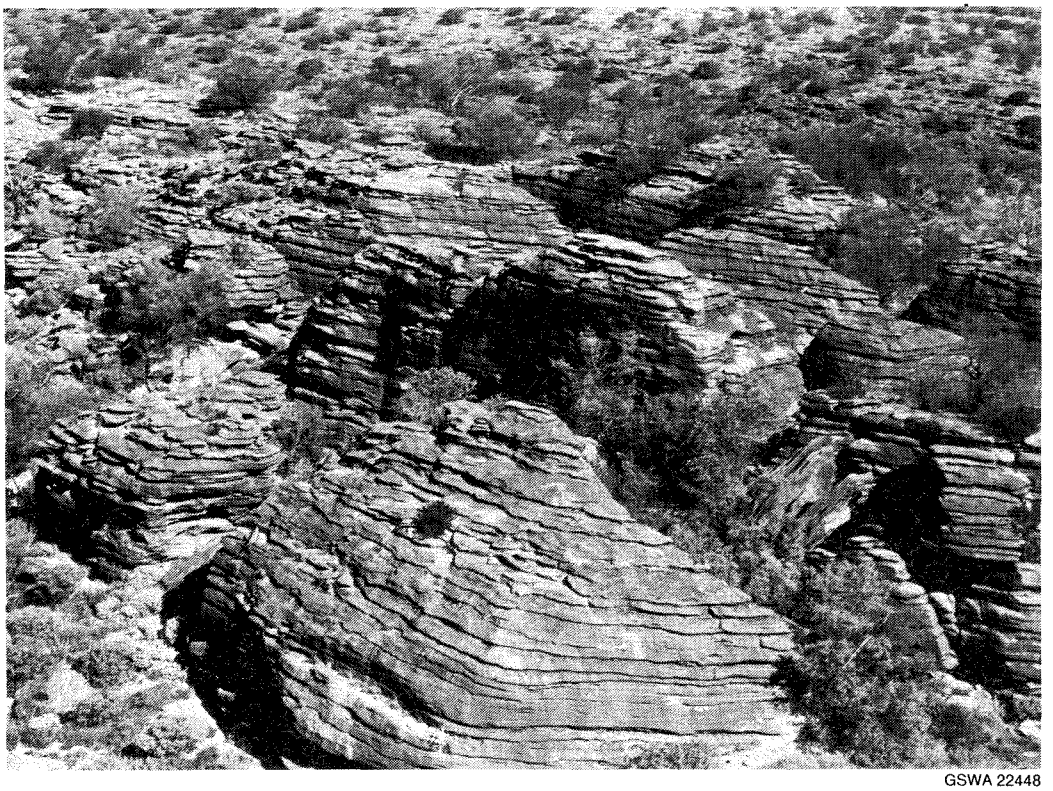

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Figure 54. Tower and corridor karst on Callytharra Formation 3 km west of Coronation Bore, Bidgemia. Only minor remnants of Moogooloo Sandstone remain in corridors.

valves, nautiloids, ammonoids, corals, blastoids, crinoids and bryozoans. Most of the fauna appears to be allochthonous, but has not undergone prolonged transport because relatively delicate forms are little abraded or broken. Condon (1967) listed numerous forms, but noted that the fauna was not described fully.

The Callytharra Formation is late Sakmarian in age (Glenister and Furnish, 1961). Dickins (1985) showed it as occupying the entire Sterlitamakian.

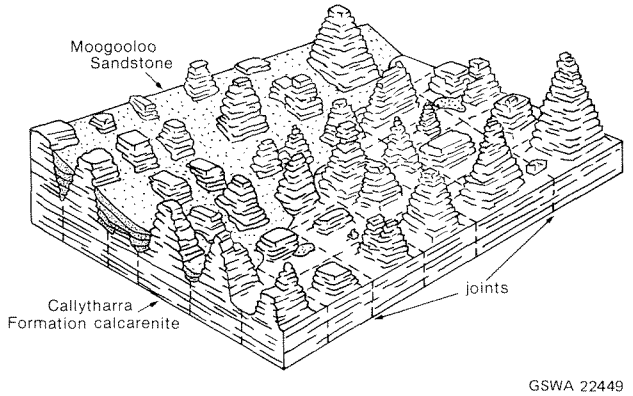

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Figure 55. Mode of occurence of karst and karst infill, based approximately on terrain visible at 24°54′, 115°27′E.

Environment of deposition

Over most of the Carnarvon Basin, the Callytharra Formation was deposited in quiet, moderately deep, marine conditions, below wave base and with dominantly fine-grained terrigenous input. No glacial erratics are known, indicating the climate had ameliorated after the previous glacial conditions.

The upper, calcarenite facies, developed in the eastern Merlinleigh and Bidgemia Sub-basins, formed in distinctly shallower more agitated water, as shoals analogous to those described by de Raaf and others (1977). There are no indications of emergence and intermittent subaerial conditions.

Deposition of the Callytharra Formation was initiated by warming of the ocean at the close of glaciation. This lessened the solubility of calcium carbonate (Revelle and Fairbridge, 1957, p. 251) so that much carbonate, previously in solution, was precipitated as lime mud and/or incorporated in invertebrate organisms. Presumably, the sea level also rose as the ice melted, producing relatively quiet moderate-depth conditions near the present basin margin.

Considered together, the facies distribution and trends in thickness of the Callytharra Formation suggest that fine-grained sediment was largely transported through shallow, near-shore areas, and deposited in deeper, offshore, quiet areas. In time, shallowing of the areas near shore occurred, and shoals of coarse-grained bioclastic debris accumulated in areas subject to wave influence. The shallowing was probably due to isostatic uplift of the basin margin and hinterland, following the melting of the Late Carboniferous to Sakmarian continental ice mass. Uplift of this nearshore area continued at the close of deposition and chemical erosion formed an area of labyrinth karst terrain.

WOORAMEL GROUP

Stratigraphy

The Wooramel Group was first named by Condit (1935), as the "Wooramel Sandstone". This was revised by Konecki and others (1958), who raised the unit to group status and named several formations within it. Other formations within the group were named by Condon (1954, 1962a, 1965b, and *in* McWhae and others, 1958). The terminology of the group in the Byro Sub-basin was simplified by van de Graaff and others (1977), and Hocking and others (1980) revised some of the remaining names. The group is a siliciclastic sequence, which disconformably overlies older rocks and is conformably overlain by the Byro Group. It consists of the Cordalia Sandstone, Moogooloo Sandstone, Keogh Formation, and Billidee Formation. It is characterized by the presence of medium- and coarse-grained sandstone with minor conglomerate, unlike the overlying Byro and Kennedy Groups which are mostly finer grained. The Keogh and Billidee Formations are laterally equivalent, with the former restricted to the central and southern Byro Sub-basin and the southern Merlinleigh Sub-basin.

Depositional setting

In the early Artinskian, (perhaps most of the Aktastinian), the onshore Carnarvon Basin was largely emergent and subject to erosion. The unconformity can be verified in the eastern sub-basins, but not in the Gascoyne Sub-basin where little of the Permian sequence is preserved. Deposition recommenced in the mid-Artinskian, coincident with a major transgression. The palaeoslope, as determined from dominant palaeocurrent directions in the Wooramel Group, was to the northwest.

In a major progradational episode, the Wooramel Group built westwards over the Callytharra Formation. In the Byro, Bidgemia and eastern Merlinleigh Sub-basins, the Moogooloo Sandstone formed a prograding wedge resting directly on the Callytharra Formation. Conditions were terrestrial to very shallow marine, with deposition in low-sinuosity braided-fluvial and delta-plain channel and (to a lesser extent) interchannel environments. In deeper parts of the basin to the west and northwest (where water depth was sufficient), the Cordalia Sandstone was deposited on the Callytharra Formation. Deposition of the Cordalia Sandstone took place in offshore to shoreface environments, forming a prodelta sequence. The Moogooloo Sandstone continued to prograde, over the Cordalia Sandstone, and formed a diachronous sand sheet. This sheet was deposited in delta-front and distributary-channel environments, and rested on a westwards-thickening prodelta sequence. Both the delta front and delta plain were largely fluvial dominated, in the sense of Elliott (1978), and little material can be recognized from interdistributary areas of the delta plain or front.

Progradation then largely ceased as a result of the continuing transgression and a lessening of terrigenous input, and the Billidee Formation formed in tidal-flat to low-energy marine-shelf environments. Some areas of the shelf were shallower and subject to more wave action. Shoaling episodes took place, forming the Jimba Jimba Calcarenite Member and facies equivalents (in the Bush Creek Syncline, and between Miller Bore and Mount Sandiman shearing sheds). These shoaling episodes were followed by local lobate-delta building, best seen west of Miller Bore. In the central and southern Byro Sub-basin (and possibly west of the Carrandibby Inlier), higher energy levels prevailed than further north, and a lateral equivalent of the Billedee Formation, the Keogh Formation, was deposited in sub-tidal, tidal-flat and deltaic environments.

The depositional environments of the Wooramel Group are difficult to assess in the subsurface to the west and north of outcrop areas. The limited amount of data from petroleum-exploration wells and coal-exploration boreholes suggest that deposition was primarily in marine-shelf to offshore environments, with a higher energy peak during deposition of the Moogooloo Sandstone, at the time of maximum progradation. Thin coal seams are present in the Billidee Formation and Moogooloo Sandstone in Quail 1, indicating delta-plain conditions this far west, at least for a short time. The coal seams are in the

middle of the Billidee Formation, as are the small deltas near Miller Bore, and together suggest a minor regression.

Lavering (1984) summarized the development and geometry of the lower part of the Wooramel Group on KENNEDY RANGE and WINNING POOL.

CORDALIA SANDSTONE

Definition

The Cordalia Sandstone ("Cordalia Greywacke" of Condon, 1954; amended by Hocking and others, 1980) is the fine-grained sandy to silty sequence conformable beneath the clean sandstone of the Moogooloo Sandstone and unconformable on the Callytharra Formation. The type section is 7 km north of Cordalia well, about 1 km south of the Lyndon River. This section is not well exposed, and reference sections illustrating lithological changes are shown in Figure 56.

Lithology

In outcrop the Cordalia Sandstone is a coarsening-upward sequence from silty, very fine-grained sandstone or siltstone to silty fine-grained sandstone. Grain size coarsens upwards from very fine sand or silt, near the base of the formation, to fine or medium sand near the top. Mica flakes are common in several sections. The unit is characterized by the silty, unwinnowed nature of the sandstone and generally fine grain size. Most sandstone is quartz wacke and lithic wacke, with minor quartz arenite.

Bedding within the unit, though commonly obscured or obliterated by bioturbation, is generally thin to laminated, on a 0.5 to 5 cm scale. It is horizontal to rippled, with some festoon cross-lamination, and generally thickens upwards. Trails, especially *Scalarituba*, are common on bedding surfaces.

Gypsum, secondary after pyrite, is locally present. Concretionary ferruginous nodules also occur, and probably developed as "case-harden-

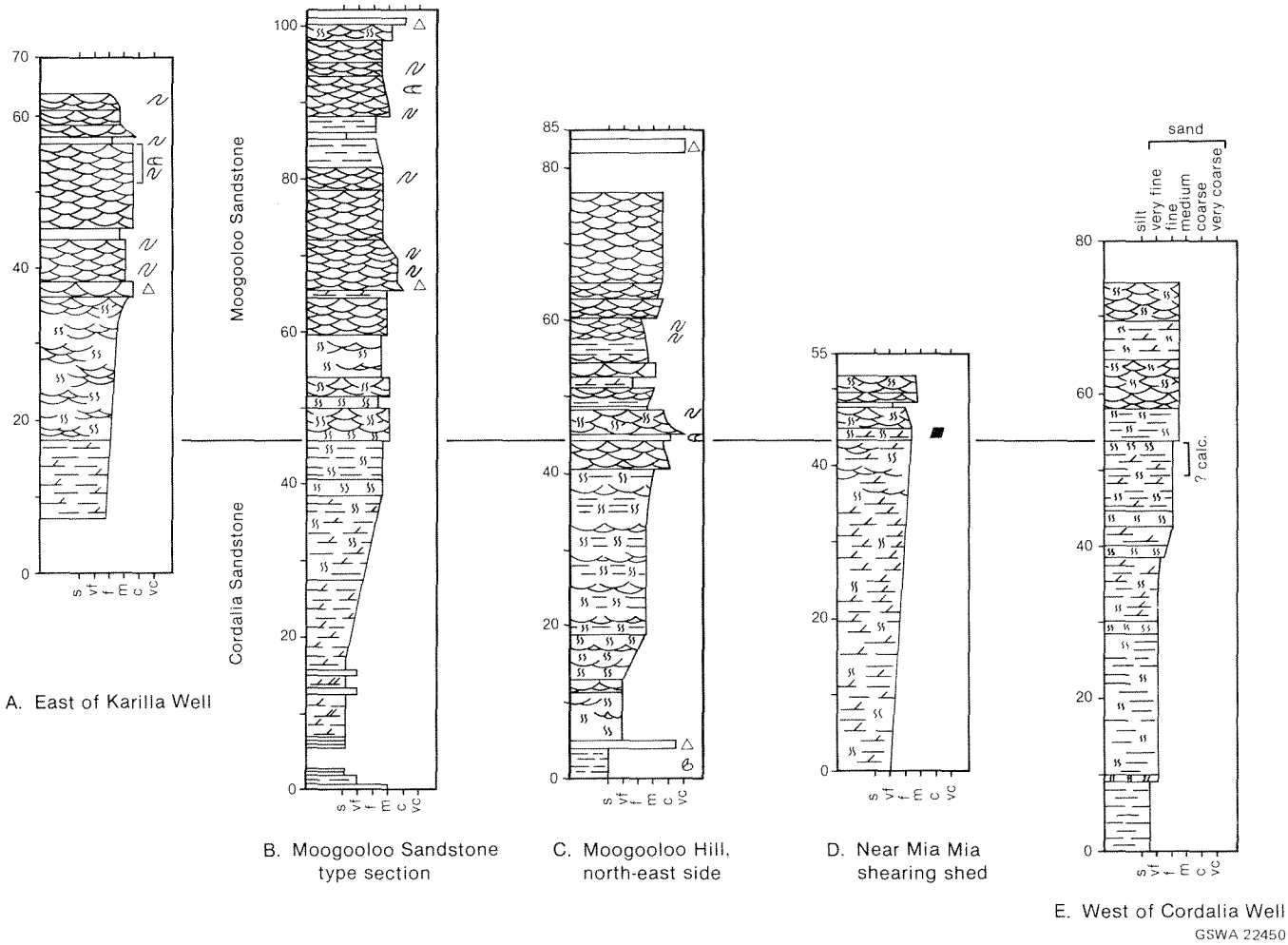

Figure 56. Measured sections of Cordalia and Moogooloo Sandstones, Gooch Range area.

ing" of fossils. Nodular pyrite in Remarkable Hill 1 (Berven, 1969) may be the subsurface expression of these concretions.Take in Figure 56

The base of the unit is commonly marked by a thin (less than 2 m) bed of quartz sand and granules, containing fragmented fossils derived from the Callytharra Formation. This is a lag deposit of unconsolidated material from the unconformity surface. In the bluff west of Cardalia Well (Fig. 56), intensely ferruginized beds 20–40 cm thick are present between pallid bioturbated silty sands in the uppermost 5 m of the Cordalia Sandstone: these originally may have been limestones.

Distribution and thickness

The Cordalia Sandstone is developed continuously north and west of Mundarrie Well (Middalya), and is locally present, but less than 1 m thick, in the outcrop belt down the eastern side of Kennedy Range. It has not been recognized east of the Lyons River and south of the Gascoyne River. Immediately east of Karrilla Well (Middalya), the formation is 17 m thick. It thickens westwards and northwards as follows: 46 m near the Moogooloo Sandstone type section; 44 m immediately east of Moogooloo Hill; 53 m west of Cordalia Well; 60 m in Quail 1; 97 m in Burna 1 (Percival and Cooney, 1985); 125 m in Remarkable Hill 1; and 138 m in Giralia 1.

The Cordalia Sandstone probably was deposited over most of the Gascoyne Sub-basin, but the Permian sequence isolated areas such as the Giralia Anticline and in Learmonth 1. In Onslow 1 the Cordalia Sandstone is absent (Jones, 1967), although the overlying Moogooloo Sandstone is present, which suggests closure of the Permian basin to the north.

Fossils and age

A reasonably varied ichnofauna is present in the Cordalia Sandstone, but the only recorded body fossils are an ammonoid, fragmental brachiopods, and bryozoans. Condon (1965) noted that the brachiopods and bryozoans may be reworked from the underlying Callytharra Formation: we agree. The ammonoid *Pseudoschistoceras simile* was recorded from the type section by Cockbain (1980), who considered that it indicated an age no older than Baigendzhinian (mid Artinskian).

Environment of deposition

The fine grain size, thin bedding and bioturbation indicate a moderate- to low-energy marine environment, with little reworking of sediment. No features suggestive of a tidal-flat environment (such as herringbone cross-stratification, desiccation cracks, and lateral facies variability) have been found. The absence of such structures, in combination with the thin bedding and bioturbation, are taken to indicate an offshore depositional environment in which little reworking of sediment took place, but in which bottom currents were able to generate ripples.

A broad overview of the depositional setting of the Wooramel Group has been given above, with the Cordalia Sandstone interpreted as a prodelta unit beneath the delta front and delta-plain deposits of the Moogooloo Sandstone. Evidence for this is based primarily on the coarsening-upwards nature of the Cordalia Sandstone and its relationship with the Moogooloo Sandstone.

MOOGOOLOO SANDSTONE

Definition

The Moogooloo Sandstone ("Moogooloo Division" of Craig, 1950; amended by Condon, *in* McWhae and others, 1958) is a predominantly sandy unit which rests either conformably on the Cordalia Sandstone or unconformably on older sediments. The upper contact is conformable with the Billidee or Keogh Formations. The 56m thick type section (Fig. 56) is located immediately east of NMF575 at the south end of the Gooch Range.

In the Byro Sub-basin, Konecki and others (1958) proposed the names, "Congo Formation", "Monument Formation", "Nunnery Sandstone", "One Gum Formation" and "Curbar Formation" for units within the Wooramel Group. These names were discarded by van de Graaff and others (1977) because they are partially or totally synonymous with either the Moogooloo Sandstone or the Keogh Formation.

Lithology

The Moogooloo Sandstone consists of fine- to coarse-grained quartz arenite and quartz wacke, with lesser amounts of conglomerate and siltstone locally present. Grain size decreases to the west (Figs 56 and 57). In the Byro Sub-basin, the formation is a coarse- to medium-grained, poorly to moderately sorted quartz arenite or quartz wacke, with common pebble beds and stringers. Locally, there are significant silty intervals and platy clay intraclasts derived from the erosion of desiccated clay interbeds. In the Bush Creek Syncline the unit is dominantly granule and pebble conglomerate,

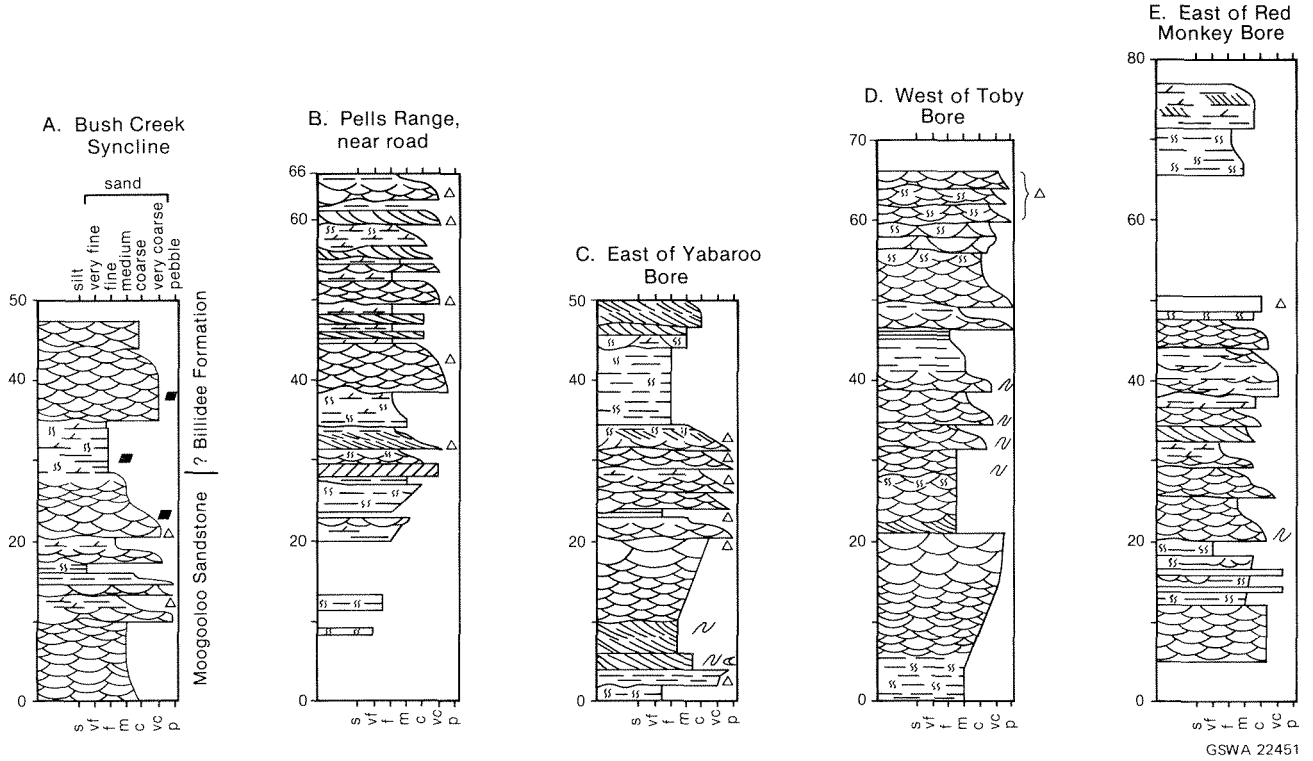

Figure 57. Moogooloo Sandstone measured sections in eastern Merlinleigh and Bidgemia Sub-basins. Section A, the "type section" of Condon's "Congo Formation", has a faulted base and top, and minor internal faulting.

with lesser coarse- and medium-grained quartz sandstone. In the eastern Merlinleigh Sub-basin, along the eastern face of Kennedy Range, the unit is dominantly medium- and coarse-grained quartz sandstone with lesser pebbly intervals and common silty interbeds, often at the tops of fining-up cycles (Fig. 57). McGann (1974) described the petrology of the Moogooloo Sandstone in a small area near Lyons River homestead. Further to the north and west, in the Gooch Range, the Moogooloo Sandstone is a uniform, well-sorted, medium-grained, sparkling quartz arenite, with minor quartz and feldspathic wacke and siltstone (Fig. 56).

The dominant bedding type is trough cross-bedding, with lesser amounts of horizontal bedding and planar cross-bedding, and minor ripple lamination. Bioturbation is generally restricted to finer grained, horizontally bedded portions. Locally it obliterates bedding.

Deformed cross-bedding, both parabolic recumbent and contorted (Doe and Dott, 1980), is common in the Moogooloo Sandstone, particularly in the Gooch Range and as far south as Red Monkey Bore. It is most common at or near the base of fining upwards cycles (Figs 56, 57). Bioturbated, finer -grained sediments commonly underlie contorted layers, but bioturbation has only been noted in intimate association with contorted bedding in Moogooloo Hill. This suggests that the contortion is, in general, restricted to fluvial-dominated parts of the Moogooloo Sandstone. Major gravity sliding and contortion occurred in the Byro Sub-basin, near Mintahalla Bore (Fig. 58).

Palaeocurrent data, from trough cross-bedding and rare primary-current lineation, indicate a northwesterly direction of sediment transport. Although the maturity of the sandstone and the amount of bioturbation both increase to the northwest, indicating increasing marine influences, there is little evidence of reworking of the Moogooloo Sandstone by southerly or easterly palaeocurrents originating from marine processes.

In Quail 1, Remarkable Hill 1 and Giralia 1, the Moogooloo Sandstone appears little different from outcrops in the Gooch Range, with the understandable difference that silty units and thin coaly intervals are more apparent and are not obscured by the vagaries of weathering in outcrop. In Onslow 1, the Moogooloo Sandstone is composed of fine-grained, well-sorted, feldspathic and kaolinitic sandstone.

Distribution and thickness

The Moogooloo Sandstone is exposed in the Byro, Bidgemia and Merlinleigh Sub-basins between the Lyndon River to the north and Lake

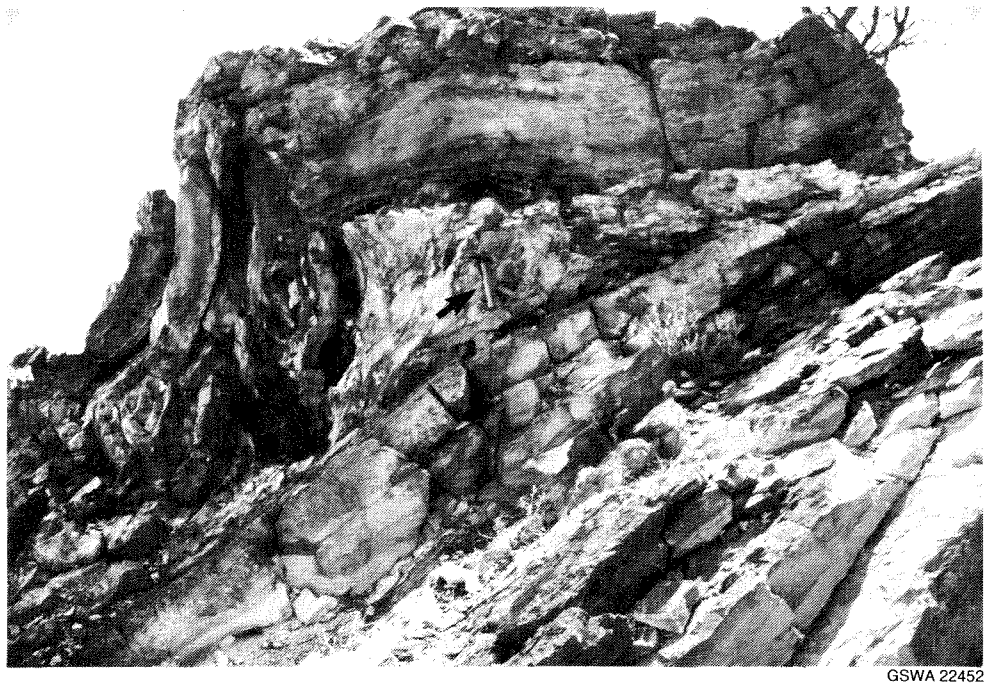

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Figure 58. Large gravity fold in fluvial Moogooloo Sandstone, Mintahalla Bore area. Note basal discontinuity. Locality is adjacent to basin-bounding fault.

Brebrele to the south, and has been recognized in the Gascoyne Sub-basin in Remarkable Hill 1 and Giralia 1, and on the Peedamullah Shelf in Onslow 1. The overlying Byro Group is present at the base of Learmonth 1. In outcrop, the Moogooloo Sandstone varies in thickness between about 30 and 70 m, with a maximum on the east side of Kennedy Range of 77 m, immediately east of Red Monkey Bore. Percival and Cooney noted a thickness of 128 m in the Jimba Syncline west of Gascoyne 1, which seems excessive compared to the 53 m in Gascoyne 1: there may be unrecognized fault repetition. In the subsurface, there is a pronounced westwards thickening, with thicknesses of 83 m in Burna 1 (Percival and Cooney, 1985), 113 m in Quail 1 (Pearson, 1964), 117 m in Remarkable Hill 1 (Berven, 1969), and 118 m in Giralia (Johnstone, 1955). However, the sandstone thins to the north, and is only 12 m thick in Onslow 1 (Jones, 1967). It is absent in Direction Island 1, where Upper Permian sediments rest directly on the Lyons Group.

Fossils and age

Fossils are rare in the Moogooloo Sandstone. Condon (1967) noted fenestellid bryozoans, brachiopods, crinoid ossicles, and wood. The formation is probably Baigendzhinian in age, because of its position between the Cordalia Sandstone and Billidee Formation (Cockbain, 1980).

Environment of deposition

The palaeocurrent data and lithotypes in the Moogooloo Sandstone indicate that deposition was dominated by fluvial processes throughout the area of outcrop. In the Bidgemia and Byro Sub-basins, trace fossils and body fossils are rare, suggesting that only very minor marine incursions took place: virtually all deposition was in a braided-fluvial environment.

In the eastern Merlinleigh Sub-basin, fluvial processes still dominated but there was slightly greater marine influence, indicated by an increase in the abundance of trace fossils. Further to the northwest in the Merlinleigh Sub-basin, the sorting of the Moogooloo Sandstone improves and the amount of bioturbation increases, but palaeocurrents were still northwestward. This suggests some winnowing of the unit, possibly in a fluvial-dominated, delta-front setting. This is consistent with a delta-plain interpretation for the Moogooloo Sandstone in the eastern Merlinleigh Sub-basin. The lack of fine-grained interdistributary material may be due to a high rate of supply and sparse vegetation (because of a cool, periglacial climate), with sediments being constantly reworked. The carbonaceous material known from the Moogooloo Sandstone indicates that some delta-plain swamps were preserved.

BILLIDEE FORMATION

Definition

The Billidee Formation was defined by Condon (1962a) as the siliciclastic, arenaceous unit resting conformably between the Moogooloo Sandstone and Coyrie Formation. The type section is west of Toby Bore, on Moogooree Station, and much of it is poorly exposed (Fig. 59C). Remeasurement along a slightly different line to that shown by Condon (1967, Fig. 78) suggests that it is about 90 m thick, rather that 73 m as stated by Condon. A bioclastic calcarenite-calcirudite facies is known from four localities, at different levels within the Billidee Formation; in the Jimba Syncline it has been named the Jimba Jimba Calcarenite Member.

Jimba Jimba Calcarenite Member

The Jimba Jimba Calcarenite was defined by Condon (1965b) as the calcareous unit lying conformably between the Moogooloo Sandstone and Billidee Formation, with known occurrences in the Jimba Syncline (where the 61 m thick type section is present) and in BMR 8 (Mount Madeline) between 143 and 161 m. At that time, these were the only known localities of a bioclastic-limestone facies in the Wooramel Group, although Condon (1967) noted that other possible exposures may have been mapped wrongly as Callytharra Formation in structurally complex areas. Since then, Gascoyne 1 intersected 73 m of the unit, near the type section. No other occurrences are known in this stratigraphic position, but sediments of identical facies were found in the middle of the Billidee Formation south of Mount Sandiman shearing sheds, and at the top of the Billidee Formation south of Red Ochre Bore on Dairy Creek Station. At the first locality, the limestones are contained within an interval 25 m thick, but at the second locality less than 5 m is exposed in a few small outcrops covering a very small area.

These occurrences are clearly related and represent a specific environment within the Billidee Formation depositional setting. This led Hocking and others (1980) to give the Jimba Jimba Calcarenite member status within the Billidee Formation, with the name applicable to the occurrences recognized by Condon (1967). The two other localities are considered as facies equivalents of the member, and are not separately distinguished as named members. Descriptions and interpretations, which follow, apply to these facies equivalents as well as to the named Jimba Jimba Calcarenite Member. The member and its facies equivalents are identical to the Callytharra Formation, and can only be distinguished from it by their stratigraphic position.

A fine-grained and a coarse-grained facies are present. The fine-grained facies consists of siltstone and fine-grained quartz wacke, grading locally to calcilutite. It is soft, fossiliferous, and south of Mount Sandiman shearing sheds is only seen as fine-grained ferruginous scree. Interbedded with the fine-grained facies (and providing the criteria for recognizing the member) is a coarse-grained facies consisting of hard, fossiliferous calcarenite grading to bioclastic calcirudite. It is mostly yellow or greenish grey, locally brown or reddish, and south of Mount Sandiman contains moderate amounts (less than 10%) of coarse, gritty quartz sand. Rugose coral fragments up to 20 cm long and 2 cm diameter are common south of Mount Sandiman.

In the Jimba Syncline, the coarse-grained facies comprises most of the sequence. Near Red Ochre Bore, a few small outcrops of the coarse-grained facies are present, with a total thickness of less than 5 m. South of Mount Sandiman shearing sheds, the fine-grained facies is dominant, and the coarse-grained facies forms discontinuous lenses up to 3 m thick which extend for several hundred metres laterally.

The member and its facies equivalents formed on a marine shelf within the zone of wave action with little terrigenous input. A limited amount of coarse-grained material (mostly shells) was present and this was concentrated into shoals by wave action, much as de Raaff and others (1977) suggested for apparently similar sediments in Ireland. The size and lack of abrasion of coral and shell fragments, particularly in the Mount Sandiman locality, suggest that they were not transported very far, and raise the possibility that the shoals may have been centred on small coral-patch reefs and shell banks.

Lithology

The Billidee Formation ranges from carbonaceous shale through silty sandstone to coarse-grained sandstone and pebble conglomerate (Fig. 59). The dominant facies in the Billidee Formation is grey to black carbonaceous siltstone and silty bioturbated fine-grained quartz wacke, with discontinuous lenses and beds of fine- to coarse-grained, locally gritty, sandstone. The siltstone is generally evenly bedded or ripple laminated, and bioturbation has locally obliterated bedding. The

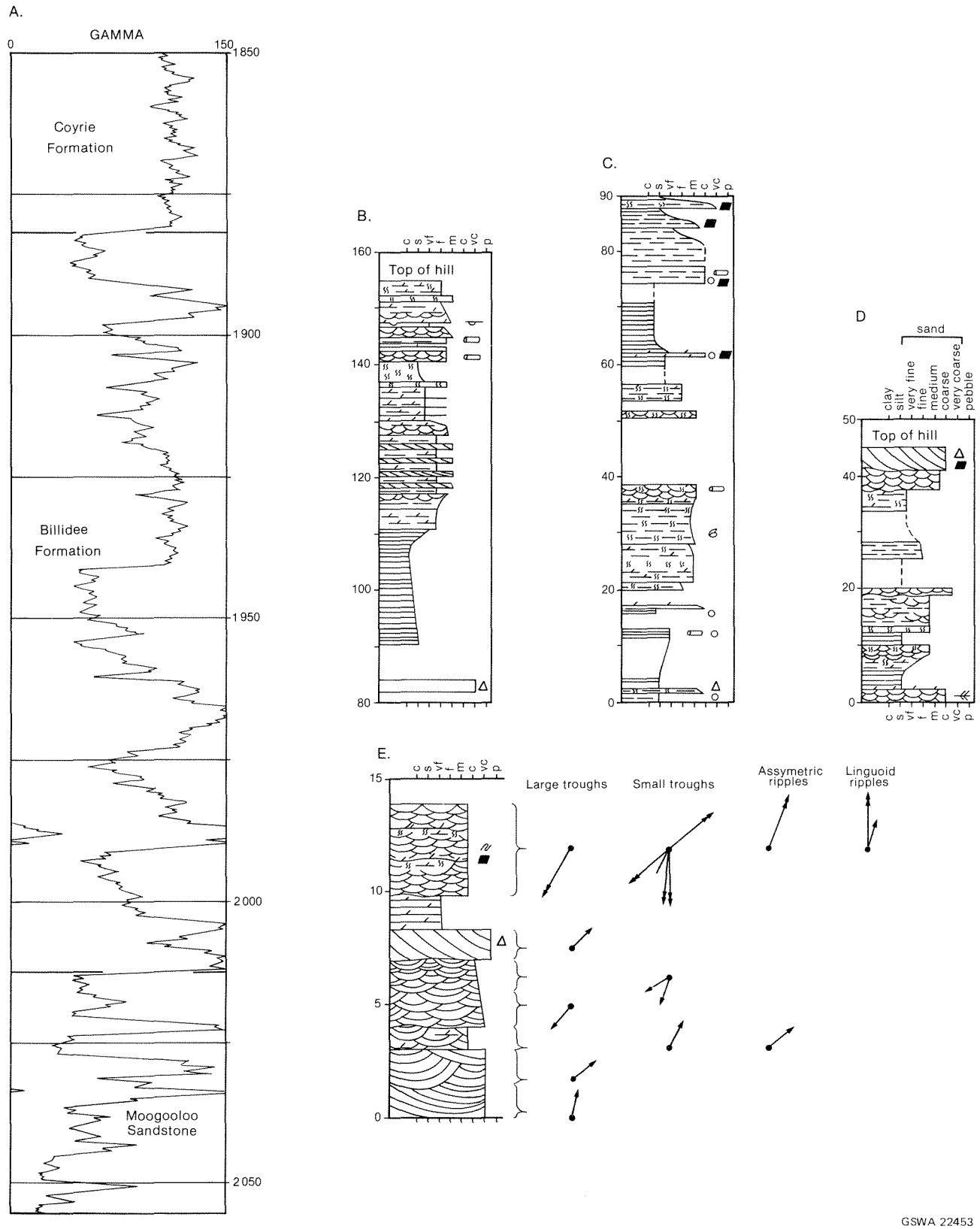

Figure 59. **Measured sections of Billidee and Keogh Formations. A. Gamma-ray log of Billidee Formation, Kennedy Range 1. Note coarsening-upward cycles below 1925 m, due to local delta progradation. B. Billidee Formation, east face of Moogooloo Hill. Thickness markings are continuous from Figure 56C. C. Type section, Billidee Formation, Toby Bore. D. Keogh Formation, Murray Peak. Note general coarsening-up at top of section. E. Partial section of Billidee Formation in Jimba Syncline. Each arrowhead indicates single palaeocurrent reading. Palaeoslope faced southwest; opposing ripples and cross-beds suggest wave-dominated delta-front setting.**

facies commonly crops out as ferruginized platy scree. Ferruginous imprints and casts of wood are common, especially in the Byro and Bidgemia Sub-basins. Intense ferruginization at some localities is thought to indicate that the siltstone was originally calcareous at these localities.

Scattered boulders, probably of glacial origin, are present in a mesa near Boonabarrie Bore and in the synclines north of Round Hill Well. Near Round Hill, they are associated with fossil wood and are clearly part of the Billidee Formation and not a later deposit.

Gypsum is locally present within finer parts of the Billidee Formation. In the Lyons River area, McGann (1976) interpreted this as primary gypsum, but a secondary origin is equally probable.

Interbedded intervals of sandstone consist of quartz and feldspathic wacke and arenite, fine- to coarse-grained and commonly with a calcareous cement. Bedding, where visible, is low- to medium-angle trough cross-stratification, with some rippled intervals. Bioturbation is locally apparent.

Coarsening-upward cycles were observed at several localities in the Kennedy Range area. In the Jimba Syncline and west of Miller Bore (Mount Sandiman), sequences up to 50 m thick coarsen upwards from bioturbated siltstone to coarse-grained sandstone or pebble conglomerate. The sandstone is predominantly medium to large scale trough and planar cross-bedded. Palaeocurrent data indicate generally westwards progradation with a secondary eastwards mode (Fig. 59E). Rippled surfaces cap some troughs. Coarsening-upward cycles occur east of Meads Bore (Mount Sandiman). Each is 10 to 15 m thick, passes from greyish-white bioturbated siltstone into linsen bedded and rippled sandstone, and is capped by 0.5 m of granule conglomerate. They are also well developed in Kennedy Range 1 (Fig. 59A).

Repeated fining-upward cycles, from medium-grained sandstone to siltstone, are present in the small anticlines between Cardigo and Four Corners Bore, Mia Mia. They have not been noted elsewhere, and lie within a dominantly fine-grained sequence of Billidee Formation.

McGann (1974) described the petrology of the Billidee Formation in a small area near Lyons River homestead.

Distribution and thickness

The Billidee Formation is exposed between Mia Mia and Coordewandy Stations, and has been recognized in Quail 1, Giralia 1 and Remarkable Hill 1. The section in Onslow 1 between 2643 and 2695 m probably correlates with the Billidee Formation. Condon (1967) discussed the thickness of the Billidee Formation in some detail. It is mostly between 60 to 90 m thick, with a maximum measured thickness of 150 m on the Lyndon River near Mia Mia homestead (although this is difficult to verify because of poor outcrop). Thicker sections appear to be present near Mount Sandiman shearing sheds and in the Jimba Syncline, but the nature of the outcrop and faulting precludes thickness determination.

Fossils and age

The Billidee Formation is sparsely fossiliferous, with fauna which includes crinoids, brachiopods, bivalves, gastropods, nautiloids, ammonoids and bryozoans. These have not been studied in detail. Silicified and ferruginous wood is present, and is more common in the Bidgemia Sub-basin and the lower part of the Billidee Formation. Trails and burrows are present throughout the unit, but do not include easily recognized, environmentally specific forms. Glenister and Furnish (1961) suggested the Billidee Formation was Artinskian, based on ammonoids.

The Jimba Jimba Calcarenite Member is richly fossiliferous, and its fauna has not been studied in detail. The assemblage is very similar to that from the Callytharra Formation, and the two units cannot be satisfactorily distinguished on macrofaunal grounds. The brachiopod and molluscan faunas of both units belong to the same Permian faunal stage of both Runnegar (1969) and Waterhouse (1970) (Fauna II and the *Stephanoviella-Taeniothaerus* fauna, respectively) and cannot be used to distinguish the units (Cockbain, 1980).

Environments of deposition

Interpreted depositional environments for the Billidee Formation, in small areas, range from offshore-marine to deltaic and tidal. McGann (1976), studied a small area between Lyons River homestead and Greys Creek and he concluded that the Billidee Formation was deposited in shallow, nearshore conditions, with occasional subaerial exposure and an alternation between stagnant anaerobic conditions and periods of strong northerly current flow. Twenty kilometres to the north, west of Miller Bore, a local deltaic environment was present, with coarse sands prograding over offshore silt and carbonate shoals to form a major coarsening-upward cycle. Progradation was westerly to southerly, reflecting local rather than re-

gional palaeogeography, and the subordinate easterly palaeocurrent data suggest the delta was wave-dominated. Lesser coarsening-upward cycles just to the south (east of Meads Bore) formed adjacent to the delta, and represent progradation from an offshore environment to (possibly) a shoreline, breaker-zone environment (represented by the thin granule layers). Coarsening-upward cycles in the Jimba Syncline, again above carbonate shoals, are also considered to be of wave-dominated delta-front origin (Fig. 59E).

Other than near Miller Bore and in the Jimba Syncline, the Billidee Formation can be related to one of two depositional settings: a tidally influenced marine-shelf to offshore-marine environment, and a tidally dominated delta-plain environment. Both are primarily low-energy environments and are potentially difficult to distinguish. Both consist of siltstone, shale and interbedded sandstone, and both are in part bioturbated, with sandstone horizons ranging from fine-grained to coarse-grained and gritty.

The presence of coal within the Billidee Formation in the Wandagee area (Pearson, 1964; Broken Hill Proprietary Company Ltd, 1976a, b, c) and indications of subaerial exposure near Lyons River (McGann, 1976) suggest a delta-plain environment, in which fine-grained sediments formed in interdistributary areas and sandstone horizons formed in distributary channels. Lenticular to flaser bedding and local herringbone cross-bedding suggest the delta plain was tide-dominated. Fining-upward sequences between Cardigo and Four Corners Bores, on Mia Mia Station, resemble channel deposits described from the Niger Delta by Elliot (1978b).

Glacial erratics such as are present near Boonabarrie Bore and Round Hill Well are not readily explained by the delta-plain setting. We consider it more likely that these were deposited in a marine-shelf environment, by scattered icebergs spalling off alpine glaciers. Sandstone interbeds in this setting represent tidal sand ridges and shoals, like those described by de Raaff and others (1977), Walker (1979) and Johnson (1978). The shelf may have been close to the coastline, as facies do not appear to be laterally persistent over large distances, and fossil wood is locally abundant. The carbonate shoals of the Jimba Jimba Calcarenite Member are also best related to a marine-shelf environment, and a fuller interpretation is given in the section on the member.

During deposition of the Billidee Formation there was a complex interplay of terrigenous supply, energy levels, water depth and (probably) differential basin subsidence, which resulted in a unit with considerable lateral and vertical variability. Compared with the Moogooloo Sandstone, the Billidee Formation shows a lessening of terrigenous input and greater influence by marine processes, in particular tides.

KEOGH FORMATION

Definition

The Keogh Formation was named by Konecki, Condon, Dickins and Quinlan (*in* McWhae and others, 1958) and first described fully by Konecki and others, 1958). It is a lateral equivalent of the Billidee Formation in the southern Carnarvon Basin adjoining the Yilgarn Block, and is distinguished from the Billidee Formation primarily by its marginally coarser grain size. The type section of the unit is near Keogh Hill and is 44 m thick.

The Keogh Formation includes most of the "One Gum Formation" of Konecki and others (1958) and the upper part of the "Curbur Formation".

Lithology

In outcrop the Keogh Formation varies from clayey siltstone through silty fine- to coarse-grained sandstone to granule and pebble conglomerate (Fig. 59D). The lithology seen most commonly is fine- or medium-grained quartz and feldspathic wacke. In well-exposed sections (as for example in Murray Peak and the type section) the formation has a sandy base, followed by a silty middle portion and a sandy top. Locally, it is difficult to distinguish from less mature portions of the Moogooloo Sandstone. Black carbonaceous shale is present in the subsurface (Mercer, 1967), but in outcrop is masked by weathering. Trough cross-stratification with lesser planar cross-stratification is generally dominant at the base and top of the formation. Cross-stratified intervals commonly have a sharp, granule-lag base and fine upwards both in grain size and bedding scale. Thin bedding and ripple bedding are dominant in the middle of the Keogh Formation. Flaser and lenticular bedding are present, and herringbone cross-stratification and reactivation surfaces are common throughout (Fig. 60). Clay intraclasts are locally present in cross-stratified portions, and bioturbation is present throughout but is best developed in the finer grained, silty, middle portion. These lithological differences form a fining-upward sequence from the upper Moogooloo Sandstone, followed locally by a coarsening-upward sequence which culminates at or near the top of the Keogh Formation.

The Keogh Formation fines northwards and grades laterally into the Billidee Formation in the Coordewandy–Plant Well area. This is expressed by the gradual northwards diminishing of the coarsening-upward sequence in the upper portion of the Keogh Formation.

Thin coaly intervals have been found in the subsurface (Mercer, 1967; Dampier Mining Company, 1973; O'Neill, 1981). These are not known from outcrop, probably because of diagenetic effects associated with Cainozoic lateritic weathering: exposure of finer grained parts of the Keogh Formation is generally poor and limited to ferruginized shaly scree.

Distribution and thickness

The Keogh Formation is exposed primarily in the southern Byro Sub-basin, where its thickness is relatively uniform, about 50 m (Condon, 1967). In the subsurface, it has been intersected only in coal-exploration boreholes, BMR 8 (Mount Madeline) and BMR 9 (Daurie Creek) (Mercer, 1967). Coal-exploration boreholes in the Yalardy–Talisker area suggest that the Keogh Formation has a similar thickness in the southern Merlinleigh Sub-basin. Here, the only exposures are in the Wooramel River gorge and surrounding Garries Lagoon, and in both areas the identification as Keogh Formation is tentative (Denman and others, 1983; van de Graaff and others, 1983).

Environment of deposition

Herringbone cross-stratification, indicative of tidal conditions, is present in most outcrops of the Keogh Formation. Additionally, cross-bedded intervals locally contain current-rippled surfaces, with current direction opposing the main cross-bedding current direction. Reactivation surfaces are present but not common. Other features are the intercalation of low- and high-energy facies in the lower Keogh Formation (bioturbated, rippled and thin-bedded siltstone and sandstone, and cross-bedded sandstone), their lateral impersistence, the nature of the cross-stratified intervals, and the presence of coaly sediments. These suggest that the lower part of the Keogh Formation was probably deposited in a tidally influenced delta-plain environment. This was similar to the depositional environment of part of the Billidee Formation, but with slightly higher energy levels and greater fluvial influence.

Wave- to tide-dominated, delta-front settings (Elliott, 1978b) were present locally during deposition of the upper Keogh Formation. This is

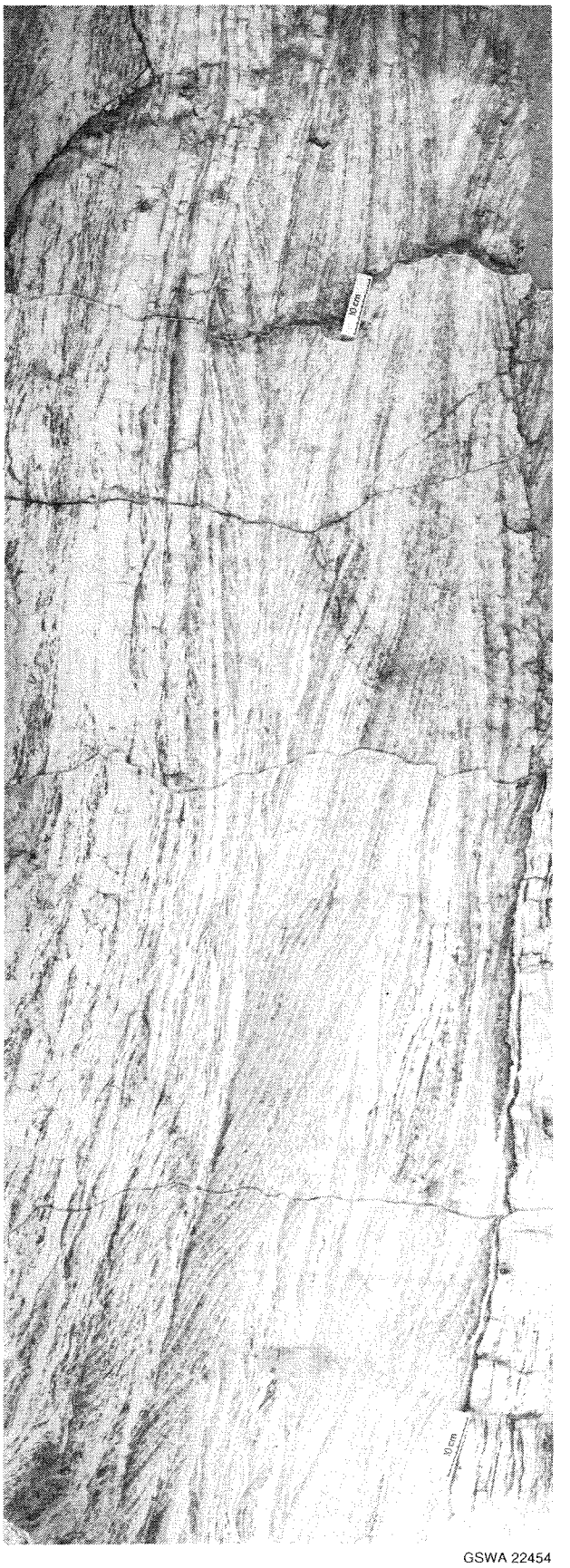

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Figure 60. Keogh Formation near type area. Fine- to medium-grained sandstone with interbedded siltstone showing cross-bedding, herringbone cross-bedding, reactivation surfaces and flaser and lenticular bedding. View from side.

indicated by coarsening-upward sequences in the upper Keogh Formation at some localities (*e.g.* Ballythanna Hill, Murray Peak), their apparent absence elsewhere, and continued evidence of opposing currents (herringbone cross-stratification, and current ripples opposing trough cross-beds). Presumably sea level continued to rise, and was balanced by supply in some areas whereas in others supply was less, and marine processes dominated. Areas of high supply may have been related to the Carrandibby Inlier, as it is known that movement took place on faults in the area during deposition of the Wooramel Group (van de Graaff and others, 1977).

Fossils and age

The Keogh Formation is only sparsely fossiliferous and no detailed study has been made of its fauna. Condon (1967) lists a few forms, including brachiopods, bivalves, gastropods, bryozoans and *Conularia*. In addition, impressions of leaves and stems are present in the lower part of the unit, and undetermined trace fossils are scattered throughout the Keogh Formation.

The Keogh Formation is of Artinskian age, based on its stratigraphic position.

BYRO GROUP

Stratigraphy

The Byro Group (Condon, 1954) is the siliciclastic sequence lying conformably between the Wooramel and Kennedy Groups, and consists of (in ascending order) the Coyrie Formation, Mallens Sandstone, Bulgadoo Shale, Cundlego Formation, Quinnanie Shale, Wandagee Formation, Nalbia Sandstone and Baker Formation. Minor amendments to the stratigraphy of the group were made by Hocking and others (1980).

The formations were originally defined on the basis of their differing faunal assemblages and varying shale-siltstone-sandstone ratios. As such, they are commonly difficult to differentiate in the field unless a signifacant portion of the sequence is present.

Some subsurface intersections of the group have been subdivided, but only informally. No attempt has been made to correlate them with outcropping formations because of the distance from outcrops and the lack of palaeontological control. Andrejewskis (1969) and Brownhill (1967) recognized the Byro Group in Flinders Shoals 1 and Sholl 1, respectively. Since then, Upper Permian and upper Lower Permian sediments in several other wells on the Cape Preston Arch have been assigned to the Byro Group. The intersections are generally dark shale and siltstone with lesser sandstone, and are thus not dissimilar lithologically. However, while these northern intersections may correlate with the group, the name should be used with caution because of the distance from outcrop and the possibility that they are locally derived deposits unrelated to the conditions responsible for deposition of the group elsewhere. This is especially true of the Upper Permian intersections assigned to the group.

Facies descriptions and interpretation

Detailed facies descriptions are presented here, rather than under formational headings, as the Byro Group is most conveniently considered as an integrated whole. The Byro Group in the Merlinleigh Sub-basin was described by Moore, Denman and Hocking (1980), and their interpretation of facies and depositional environments is followed here. Only the lower three formations of the Byro Group are present in the Byro Sub-basin, and apart from a reduction in thickness (presumably due in part to proximity to the Artinskian shoreline) they appear little different to the sequence in the Merlinleigh Sub-basin.

Two facies associations are present. The fine-grained association is divided into two facies, and the sandstone-facies association is divided into four facies, one of which contains two sub-facies. These are summarized in Figure 61, together with their abundance in the Byro Group and interpreted depositional environments.

Fine-grained facies association

The two facies recongized in the fine-grained association are a black-shale facies and a grey-siltstone facies. Both formed in conditions below storm-wave base, the first in anoxic, very quiet, restricted conditions (lower, or outer, offshore zone), and the second in less restricted, but still quiet, conditions (upper, or inner, offshore zone).

Black-shale facies: The facies is best developed in the Bulgadoo and Quinnanie Shales, with lesser amounts in the Baker Formation and the upper part of the Wandagee Formation. The facies consists of laminated, dark-grey to black shale and fine siltstone, with rare bioturbation and some small chonetid brachiopods and ostracods. The shales contain secondary pyrite and gypsum (either disseminated through the sediment or in platy bands) and ferruginous nodules up to 1 m in

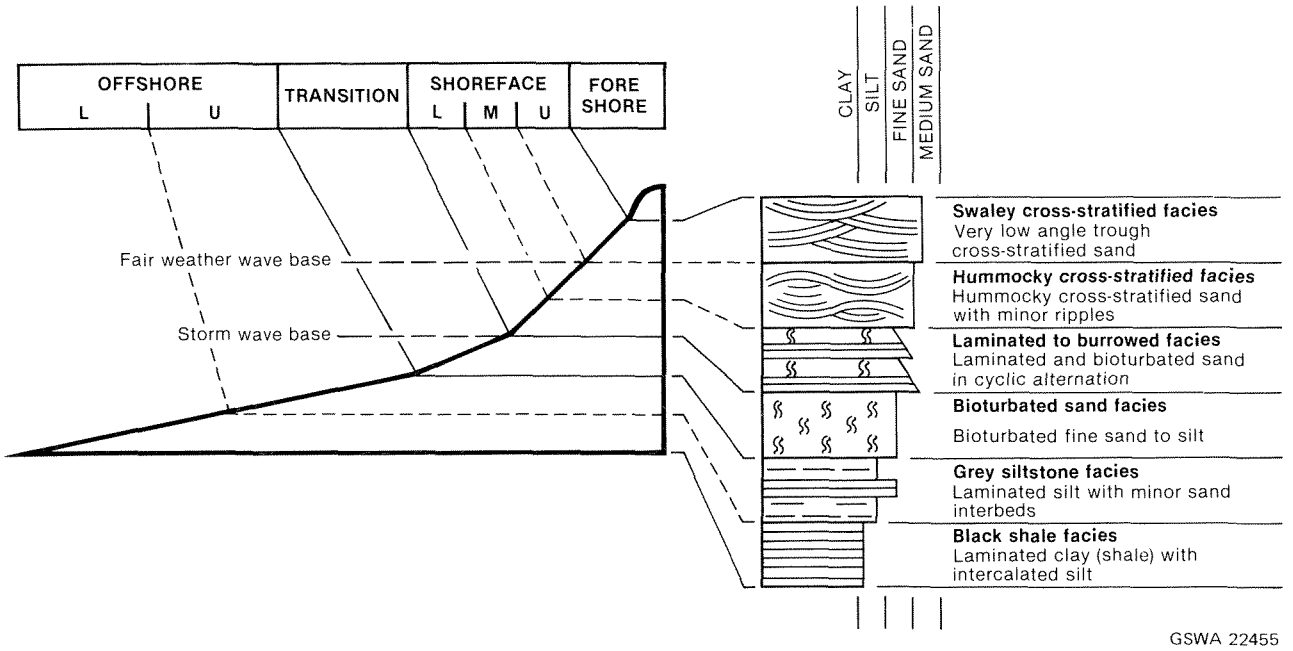

Figure 61. Depositional model showing lithofacies and interpreted environments for the Byro Group and lower Coolkilya Sandstone. Note that the shoreface is taken to the approximate base of storm-associated deep waves, rather than to fair-weather wave base.

diameter. Condon's (1967) suggestion that the gypsum is primary (p. 144) and the ferruginous nodules are mudballs formed by nuclei rolling on the seafloor (p. 165) are incorrect: both are considered by us to be of secondary origin.

The black-shale facies formed in a very quiet-water, offshore-marine environment. Significant phosphate is present (up to 1.25%, Russell, 1965), suggesting slow deposition. Restricted conditions are indicated by the phosphate, pyrite, small size of the fossils and lack of bioturbation (Heckel, 1972, p. 261). Topographic silling of the basin to achieve this effect, as suggested by Condon (1967), is not necessary.

Grey-siltstone facies: This facies characterizes the Baker Formation, especially in the eastern face of Kennedy Range, and is well developed as the lower portion of coarsening-upward cycles in Cundlego and Wandagee Formations. This facies is mainly laminated to very thinly bedded, strongly bioturbated, grey siltstone, with occasional thin sandstone interbeds and uncommon body fossils, of which most are chonetid brachiopods. Abundant small curved burrows, including *Chondrites* and *Planolites*, are present, and *Lophoctenium* has been found in thin sandstone interbeds in the Bulgadoo Shale in the Wandagee area. The ichnofauna, in particular *Lophoctenium*, is assignable to the *Nereites* ichnofacies of Seilacher (1978).

The grey-siltstone facies formed in a low-energy, offshore-marine environment with no significant wave or current activity, shorewards of the black-shale facies. Thin interbeds of planar-laminated to very low-angle cross-stratified fine sandstone, discernible in well-exposed sections, were probably introduced during major storms.

Sandstone-facies association

The four sandstone facies consist of greyish-green to brown quartz wacke, variably silty, and ranging from very fine-grained to medium-grained. They are interpreted as representing laterally adjacent sedimentary environments ranging from the transitional zone, between the shoreface and offshore environments, to (perhaps) the upper shoreface. No sediments from the foreshore zone have been found within the Byro Group.

Bioturbated-sandstone facies: This is best developed in the Nalbia and Mallens Sandstones, with thin intervals in the Coyrie, Wandagee and Cundlego Formations. It consists of poorly to moderately sorted, fine- to very fine-grained sandstone and silty sandstone in which the original even bedding has commonly been entirely obliterated by bioturbation. Two subfacies are discernible, based on the degree of bioturbation and the ichnofauna. In the first, bioturbation is intense, with abundant *Zoophycos* and other inclined and subhorizontal burrows (Fig. 62). Feed-

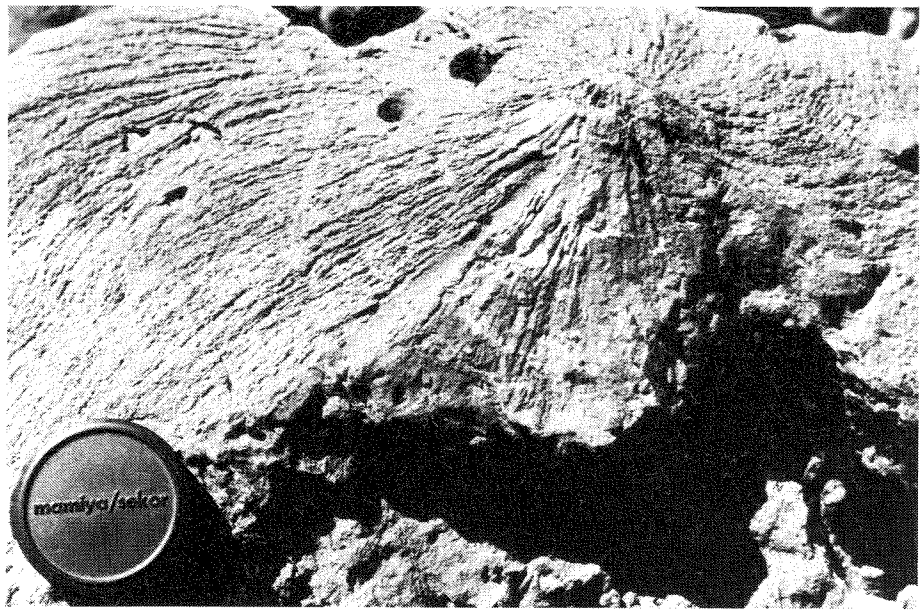

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Figure 62. ***Zoophycos*** **from central portion of Nalbia Sandstone, Blackheart Valley. Lens cap 54 mm in diameter.**

ing burrows are moderately organized and complex. The interpreted environment is a marine shelf below storm-wave base, with continuous, relatively slow sedimentation (allowing complete reworking of sediment by infaunal organisms), low oxygen levels and a soupy sediment surface.

The second subfacies is less intensely bioturbated and contains small bulb-shaped burrows which Moore, Denman and Hocking (1980, Fig. 4D) interpreted as bivalve burrows. The bivalve assemblage consists of sand-dwellers, and gastropods from this subfacies probably lived in clear water on a firm sandy seafloor (Dickens, 1963). This subfacies probably formed in slightly shallower, more energetic conditions than the first subfacies.

Laminated- to burrowed-sandstone facies: The facies is best developed in the Mallens Sandstone, with minor occurrences in the Nalbia Sandstone and Coyrie and Cundlego Formations. It consists of sharp-based couplets of (at the base) planar-laminated to very low-angle cross-stratified (?hummocky) sandstone which becomes increasingly bioturbated upwards until, at the top of the couplet, most bedding structures are destroyed. The sandstone is fine to very fine grained, moderately sorted and micaceous, and body fossils are mainly disarticulated bivalves and brachiopods.

Such sediments form at or slightly below storm-wave base, below the erosional influence of all but the largest storm waves. (Bourgeois, 1980; Kriesa, 1981). During fair weather, incoming sediment is reworked by various organisms. During storms, wave base is lowered, and a laminated layer is formed, both by increased sediment input and reworking of the substrate. After the storm, normal biogenic activity resumes and the upper part of the storm-deposited layer is bioturbated.

Hummocky cross-stratified facies: This is best developed in the Mallens Sandstone and Cundlego Formation, with lesser amounts in the Coyrie Formation and Nalbia Sandstone, and thin interbeds in the Baker Formation and Bulgadoo Shale. It consists of hummocky cross-stratified, fine-grained sandstone with abundant scour surfaces, rare trace fossils, minor ripples (on the tops of hummocky cross-stratified units) and a sparse fauna, which tends to be concentrated in lags in storm-scoured hollows (Fig. 63).

Hummocky cross-stratification in the Byro Group formed in shallow-marine conditions between fair-weather wave base and storm wave base during storms (Moore and Hocking, 1983).

Swaley cross-stratified facies: (Trough cross-stratified facies of Moore, Denman and Hocking, 1980). This facies is most abundant in the Cundlego Formation (with excellent exposures at Cundlego Crossing), with thin intervals in the Nalbia Sandstone on the eastern side of Kennedy Range and isolated swales amidst hummocky cross-stratified units in the Mallens Sandstone. The facies consists of intersecting sets of swaley cross-stratified, fine-

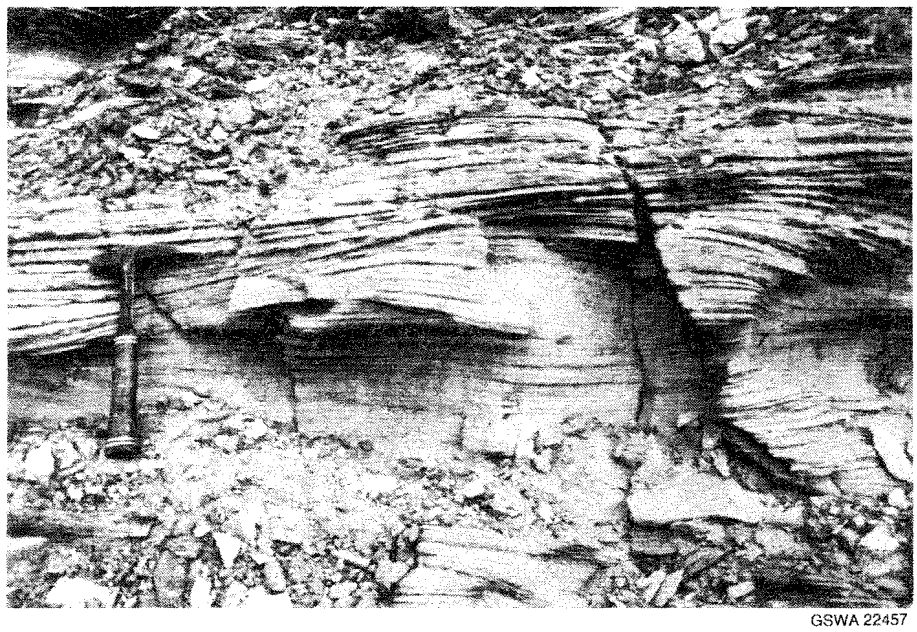

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Figure 63. Hummocky cross-stratified sandstone in basal Nalbia Sandstone, Blackheart Valley.

to medium-grained, well-sorted sandstone, with rare ripple-laminated and horizontally laminated interbeds. Minor sub-vertical burrows are the only trace fossils, and rare allochthonous bivalve and spiriferid coquinas are the only body fossils. (Fig. 64).

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Figure 64. Allochthonous, storm-concentrated coquina from swaley cross-stratified facies in Cundlego Formation at Cundlego Crossing. Coin 32 mm in diameter.

Walker (1981, p. 6.11) tentatively interpreted swaley cross-stratification as a "storm-formed structure somewhat closer to shore than HCS (hummocky cross-stratification) . . . based upon its normal stratigraphic position, above HCS and amalgamated HCS in prograding sequences", which agrees with Moore, Denman and Hocking's preferred interpretation (middle to upper shoreface) for this facies. Scattered "normal" troughs within this facies may be the products of fair-weather wave and tide currents.

Depositional setting

The relationships between the six facies of the Byro Group are shown in Figure 61, and suggest that the Byro Group was deposited in a storm-dominated marine-shelf environment. Cyclicity in the Coyrie Formation, Bulgadoo Shale, Cundlego Formation and Wandagee Formation, described by Moore, Denman and Hocking (1980, p. 59), suggests periodic subsidence during deposition of these units, with slight but abrupt regression preceding subsidence.

The storms which dominated Byro Group deposition were sub-polar, rather than the tropical cyclones which most previous workers have suggested as forming hummocky cross-stratified deposits. Evidence for this is the scattered glacial erratics, in the underlying Billidee Formation and lower Coyrie Formation in the Byro Sub-basin, and the relatively common erratics in the

Carynginia Formation of the northern Perth Basin (Playford and others, 1976), which we consider to be of glacial origin. These suggest scattered alpine glaciers at reasonably high latitudes, which agrees broadly with Embleton (1973) and Smith and others (1981) who showed the central Carnarvon Basin located at about 55° to 65°S during the Permian.

COYRIE FORMATION

Definition

The Coyrie Formation was defined by Condon (1954), and revised by Condon (1962a) to exclude the lower, sandy portion, which he named the Billidee Formation. As now defined, the Coyrie Formation is the dominantly silty interval between the Billidee Formation and Mallens Sandstone. The type section (Fig. 65) is 180 m thick and is located at the northeastern end of Kennedy Range between Toby Bore and Red Monkey Bore. Hocking and others (1980) abandoned the "Madeline Formation" in favour of the Coyrie Formation.

Lithology

The Coyrie Formation consists of interbedded grey siltstone and fine-grained greenish-grey sandstone, with minor black shale. Sandy units are commonly slightly calcareous in outcrop. Scattered glacial erratics are present in the unit in the Byro Sub-basin and near the base of the type section. Deposition took place mainly in an offshore, quiet-marine environment.

Distribution and thickness

The Coyrie Formation is exposed between the Lyndon River and Curbur Station, in the Merlinleigh and Byro Sub-basins. It has been removed by post-Permian erosion in most of the Gascoyne Sub-basin.

The thickness of the Coyrie Formation in outcrop in the Merlinleigh Sub-basin is generally about 200 m. An anomalously thick section is present adjacent to the Wandagee Fault east of Mia Mia homestead (396 m, Condon, 1967) but exposure is generally poor, and there may be substantial fault repetition of the sequence. Subsurface intersections of the Byro Group to the northwest — in Giralia 1, BMR 5 (Giralia) and Learmonth 1 — cannot be readily correlated with known formations, so the possible northwestwards thickening, implied by the section at Mia Mia, cannot be confirmed.

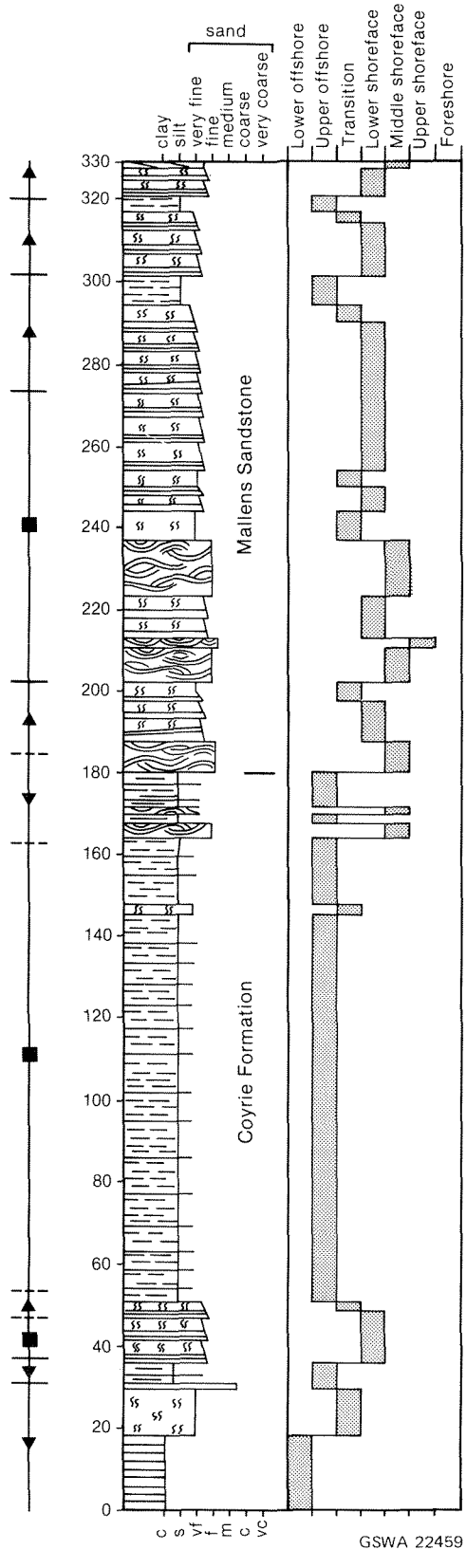

Figure 65. **Type sections of Coyrie Formation and Mallens Sandstone. Fining- and coarsening-upward cycles are indicated by arrows; no clear cyclicity is indicated by squares.**

In the Byro Sub-basin, thicknesses of between 85 and 195 m for the Coyrie Formation (as "Madeline Formation") were recorded by Condon (1967) and Konecki and others (1958). Reliable measurements of thickness are difficult to obtain because of generally poor outcrop with low dips, and these figures should be taken as a broad indication only.

Fossils and age

The Coyrie Formation contains an abundant fauna which appears to be primarily autochthonous and consists of foraminifers, bryozoans, crinoids, brachiopods, bivalves, gastropods, nautiloids and ammonoids. Plant remains and trace fossils are also present. Condon (1967) listed genera and species known to that time. Since then, Archbold (1981a) identified fish scales from the Coyrie Formation in the Byro Sub-basin, and has touched on the fauna of the Byro Group in other publications (1981b, 1981c). Glenister and Furnish (1961) dated the Coyrie Formation as Baigendzhinian (mid-Artinskian), based on ammonoids.

MALLENS SANDSTONE

Definition

Teichert (1950) named the Mallens Sandstone, and Condon (1954) established a type section for the unit at the northern end of the Kennedy Range, between Donnellys Well and Red Monkey Bore. This is shown in Figure 65. Hocking and others (1980) simplified Byro Group terminology, abandoning the name "Bogadi Greywacke" in favour of Mallens Sandstone. The Mallens Sandstone is the dominantly sandy unit between the dominantly fine-grained Coyrie Formation and Bulgadoo Shale.

Lithology

The Mallens Sandstone is most readily recognized in outcrop as a fine- to medium-grained bioturbated sandstone resting between the poorly outcropping, fine-grained Coyrie Formation and Bulgadoo Shale. Hummocky cross-stratification is common. Deposition was mainly in transition-zone, and lower- and middle-shoreface environments.

Distribution and thickness

The Mallens Sandstone can be recognized in the Merlinleigh and Byro Sub-basins, but in the Gascoyne Sub-basin, the few intersections of the Byro Group cannot be correlated with the defined, outcropping formations.

The type section of the Mallens Sandstone, as measured by Moore, Denman and Hocking (1980), is 150 m thick. In Kennedy Range 1 the formation is 197 m thick. Elsewhere in the Merlinleigh Sub-basin, poor outcrop precludes the measuring of complete sections through the Mallens Sandstone, but its thickness appears to be in the range 150–200 m. In the Byro Sub-basin, Condon (1967) gave thicknesses of about 60–110 m for the "Bogadi Greywacke". These figures are difficult to verify because of poor outcrop and gentle dips, but suggest that the Mallens Sandstone is thinner in the Byro Sub-basin.

Fossils and age

The Mallens Sandstone contains a marine fauna, dominated by bivalves which were described by Dickens (1963). Other fossils were listed by Condon (1967). Notable among the ichnofauna is *Zoophycos*, especially in the Byro Sub-basin.

The fauna is not age-specific, but the Mallens Sandstone is considered as mid-Artinskian because of its stratigraphic position between the Coyrie Formation and Bulgadoo Shale.

BULGADOO SHALE

Definition

Teichert (1941) named the "Bulgadoo Series", and Condon (1954) amended this to Bulgadoo Shale and established a type section on the Minilya River west of Wandagee homestead. The unit is the dominantly shaly sequence overlying the Mallens Sandstone. The lower part of the Bulgadoo Shale is not exposed in the type section, and the exposed section is cut by faults. Reconstruction of the section gives an exposed thickness of 154 m (Fig. 66). The "Warra Warringa Formation" from the Byro Sub-basin was abandoned by Hocking and others (1980) in favour of the Bulgadoo Shale.

Lithology

The Bulgadoo Shale consists of black, pyritic shale with very minor interbeds of fine-grained green sandstone. Secondary pyrite, gypsum, and phosphate nodules are present in some horizons. The unit was deposited under reducing conditions in a quiet, offshore-marine environment.

Distribution and thickness

The Bulgadoo Shale can be recognized in the Merlinleigh and Byro Sub-basins. Measured thicknesses are difficult to obtain because of

(generally) extremely poor outcrop and possible unrecognized faulting. Except in the main reference section (Condon, 1967, Figs 110, 111), which is 191 m thick, reliable estimates of thickness are obtained only by drilling. In Kennedy Range 1, the Bulgadoo Shale is 270 m thick, and potash-exploration drilling near Gascoyne Junction (Summers, 1966) suggests thicknesses of about 60 m, which represents a marked southeastwards thinning. Only about 50 m is exposed in the Byro Sub-basin, where post-Permian erosion has removed an unknown amount.

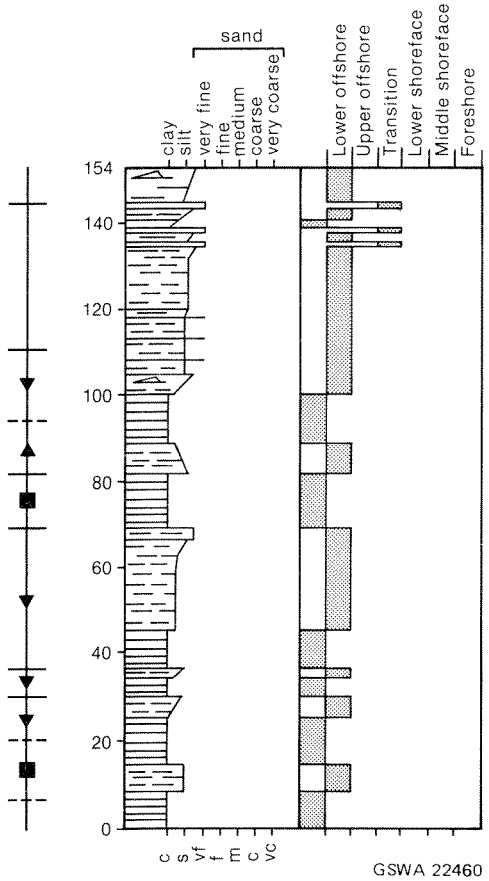

Figure 66. Type section, Bulgadoo Shale. Lower part of Bulgadoo Shale not exposed, section reconstructed by correlation over several small faults.

Fossils and age

Fossils recorded from the Bulgadoo Shale include foraminifers, bryozoans, corals, crinoids, brachiopods, bivalves, gastropods, nautiloids and ammonoids, of which *Bamyaniceras australe* suggests an Artinskian age (Glenister and Furnish, 1961).

CUNDLEGO FORMATION

Definition

The Cundlego Formation was named by Teichert (1941), and amended and defined by Condon (1954). Condon (1967) considered that the unit was disconformable on the Bulgadoo Shale, but both McWhae and others (1958) and Hocking and others (1980) considered the contact to be conformable. The type section of the Cundlego Formation is located east of Wandagee homestead near Cundlego Crossing on the Minilya River. The unit is a sandy sequence between the silty and shaly Bulgadoo Shale and Wandagee Formation or Quinnanie Shale.

Lithology

The Cundlego Formation consists predominantly of grey siltstone interbedded with hummocky and swaley cross-stratified sandstone, with little bioturbation (Fig. 67). These facies were deposited in offshore and middle-shoreface environments, possibly in a rapidly subsiding basin.

Distribution and thickness

The Cundlego Formation has only been recognized in the Merlinleigh Sub-basin, between the Minilya and Gascoyne Rivers. The stratigraphically highest sediments in the Byro Sub-basin belong to the underlying Bulgadoo Shale. As with other formations of the Byro Group, the Cundlego Formation has not been differentiated in petroleum-exploration wells which penetrated the Byro Group in the Gascoyne Sub-basin, but it is doubtful whether intersections in these wells were as stratigraphically high as the Cundlego Formation.

The Cundlego Formation appear to have a relatively uniform thickness: 374 m in the type section, 394 m in a reference section in the Minilya River near the type section (Fig. 67), 342 m in Kennedy Range 1 (Lehmann, 1967), and 412 m near Gascoyne Junction (Condon, 1967). Somewhat smaller figures given by Condon (1967) for the eastern side of Kennedy Range are considered to be due to unrecognized faulting and poor exposure.

Fossils and age

The Cundlego Formation contains a marine fauna of brachiopods, gastropods, bivalves, nautiloids, crinoids, bryozoans and foraminifers. In several locations (as for example at Cundlego Crossing) these clearly accumulated as washed-in lag concentrates in local hollows in the Artinskian sea floor (Fig. 64). The difference in fauna between the Bulgadoo Shale and Cundlego Formation, which Condon (1967) noted, is ascribed to

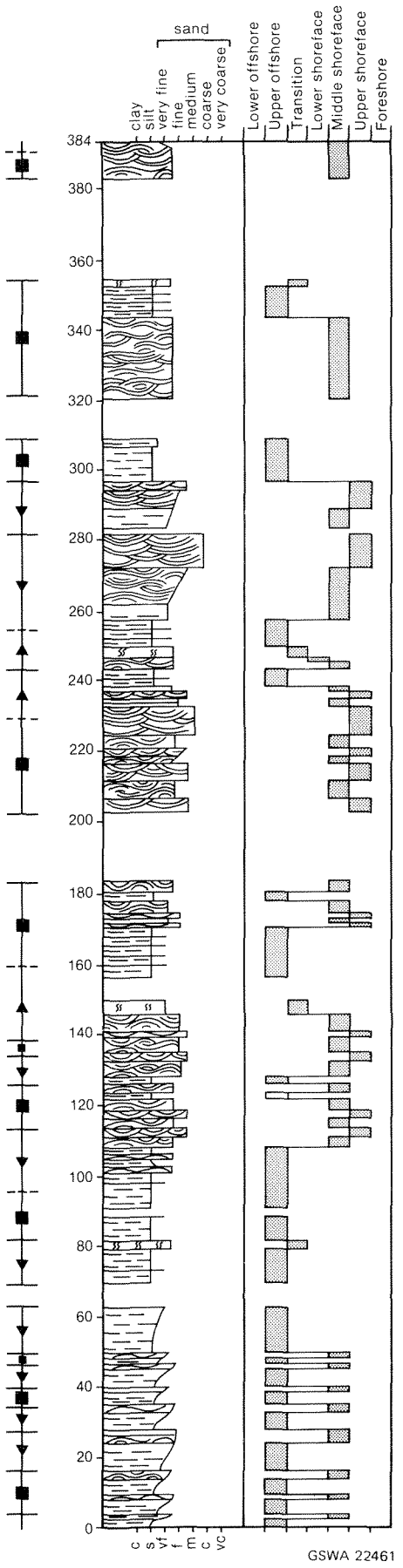

Figure 67. Cundlego Formation, Minilya River, near type section.

environmental differences, rather than to evolutionary change because of a significant hiatus in deposition.

The age of the Cundlego Formation is mid-Artinskian.

QUINNANIE SHALE

Definition

The Quinnanie Shale was named by Teichert (1950) and defined fully by Condon (1954), who established a type section on the north bank of the Minilya River at Coolkilya Pool (Fig. 68). It is a shale and siltstone sequence which has only been recognized in the Wandagee area, at the northern end of Kennedy Range and in Kennedy Range 1. The unit is thought to grade into the Cundlego Formation south of Merlinleigh homestead (Condon, 1967).

Lithology

The Quinnanie Shale consists primarily of black shale, coarsening to grey siltstone in the upper part, and was deposited in a restricted, offshore environment.

Distribution and thickness

The Quinnanie Shale has only been recognized north and west of the ruins of Merlinleigh homestead, near which Condon (1967) reported a thickness of 15 m. This thickens to 80 m in Kennedy Range 1 to the southwest (Lehmann, 1967), 30 m near Kimbers Well to the north-northwest (Condon, 1967), and 96 m in BMR 7 Muderong (Condon, 1967). In the Wandagee–Barrabiddy Creek area the Quinnanie Shale is about 100–135 m thick. This northwestwards thickening indicates deepening of the basin in this direction (possibly because of continued subsidence) with a relatively narrow shallow shelf, east of the present position of the eastern face of Kennedy Range.

Fossils and age

The Quinnanie Shale contains a sparse fauna of brachiopods, bivalves, gastropods, corals and crinoids. The ammonoid *Bamyaniceras australe* indicates a Baigendzhinian (mid-Artinskian) age (Glenister and Furnish, 1961; Cockbain, 1980). Archbold (1980) described the brachiopod *Lingula occidentaustralis*, which appears to be restricted to the Quinnanie Shale (Teichert, 1950), and interpreted a restricted environment, but con-

sidered the environment to be a tidal flat with pronounced salinity variations rather than an offshore environment. Archbold (1981b) also described other fossils from the Quinnanie Shale.

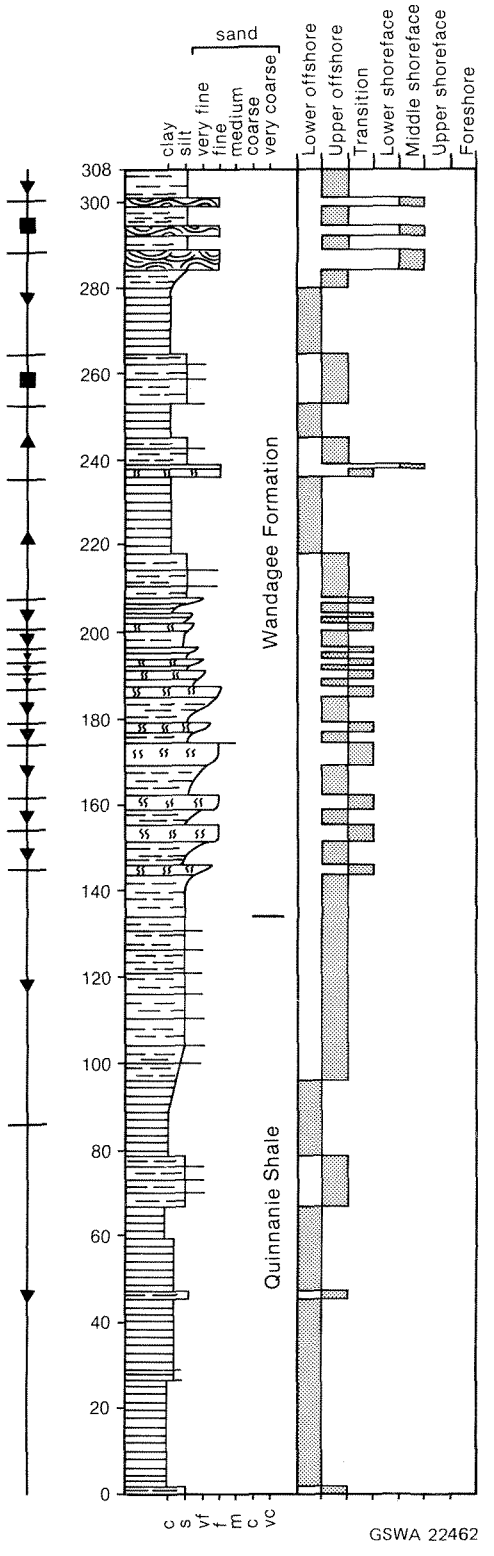

Figure 68. Type sections, Quinnanie Shale and Wandagee Formation.

WANDAGEE FORMATION

Definition

The Wandagee Formation was named by Condit (1935) and defined by Condon (1954), who designated a type section on the north bank of the Minilya River near Coolkilya Pool (Fig. 68). It is a siltstone-dominated sequence between the shaly Quinnanie Shale and the sandy Nalbia Sandstone.

Lithology

The formation is dominantly fine grained, although coarser than the underlying Quinnanie Shale. Coarsening-upward cycles from siltstone to fine sandstone characterize the lower part of the Wandagee Formation, and it fines upwards to shale and siltstone in the upper part. The formation is very fossiliferous. Stable conditions prevailed during deposition, which took place in offshore and transitional environments. Coarsening-upward cycles probably developed in response to shoreline progradation, with new cycles initiated by periodic subsidence.

Distribution and thickness

The Wandagee Formation has been recognized in the Merlinleigh Sub-basin between the Minilya and Gascoyne Rivers. The type section is 173 m thick (Moore, Denman and Hocking, 1980) and thickness varies between 202 m (in Kennedy Range) and 116 m (in BMR 6 Muderong). Condon's (1967) maximum thickness of 244 m about 8 km north of Paddys Outcamp, Middalya, is doubtful because of poor outcrop. No trend of increasing thicknesses can be discerned, and deposition appears to have been relatively uniform over the area of outcrop.

Fossils and age

The Wandagee Formation contains an abundant marine fauna, of which *Bamyaniceras australe* indicates a Baigendzhinian (mid-Artinskian) age (Glenister and Furnish, 1961; Cockbain, 1980). A faunal list was presented by Condon (1967). Archbold (1980; 1981a; 1981b) recently described some brachiopods from the unit.

NALBIA SANDSTONE

Definition

The Nalbia Sandstone was named by Teichert (1950), and later described by him in more detail (1957). Condon (1954, 1967) was reluctant to de-

fine the stratigraphic position of the Nalbia Sandstone within the Byro Group, and instead defined the "Norton Greywacke", designating a type section at the north end of Kennedy Range near Kennedy Bore. Dickins (1963) and McWhae and others (1958) considered that "Norton Greywacke" was a junior synonym of Nalbia Sandstone, and Playford and others (1975) abandoned the name. Unfortunately, the type section for the Nalbia Sandstone, some 4 km north of Wandagee Hill, is poorly exposed, with no exposed top or bottom whereas the "type section" of the "Norton Greywacke" is far better exposed throughout. This latter section, shown in Figure 69, is here considered to be the main reference section for the Nalbia Sandstone.

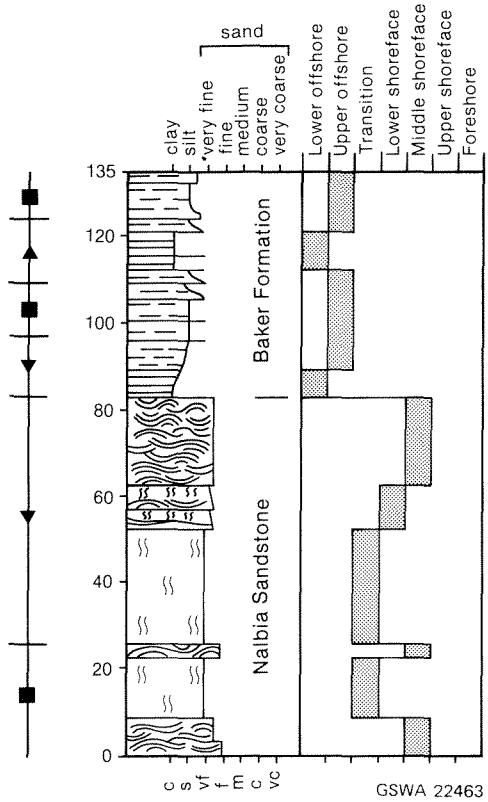

Figure 69. Reference section for Nalbia Sandstone and type section for Baker Formation, Blackheart Valley.

Lithology

The Nalbia Sandstone consists mostly of fine sandstone, with common *Zoophycos*, and lies between the silty or shaly Wandagee and Baker Formations. Deposition at the northern end of Kennedy Range was initially in a middle-shoreface environment, deepening for most of the unit to a transition-zone environment. This shallowed at the top of the formation to a middle-shoreface environment once more. Along the eastern side of Kennedy Range, conditions were shallower, with less *Zoophycos* and more hummocky cross-stratification.

Distribution and thickness

The Nalbia Sandstone outcrops in the Wandagee area, where it is generally poorly exposed, and along the northern, eastern and southern margins of Kennedy Range, where it is locally well exposed. The type section is 40 m thick (Playford and others, 1975), the main reference section, 83 m (Moore, Denman and Hocking, 1980), and the section in Kennedy Range 1, 60 m. Generally, the Nalbia Sandstone ranges in thickness from approximately 50 to 80 m, with a maximum of about 120 m in the Binthabooka Bore area (Condon, 1967). This maximum is at the most southeasterly extent of the unit where the facies suggest the shallowest depositional conditions. Sedimentation was evidently more rapid in these shoreface conditions than in the deeper environments to the north and west.

Fossils and age

The Nalbia Sandstone is notable for numerous and large (approximately 40 cm diameter) *Zoophycos*, as well as other undetermined trace fossils and a locally abundant marine fauna. As with other formations in the Byro Group, shells are commonly found as lag concentrates in hollows and on bedding planes. Condon (1967) listed the forms identified to that time, and Archbold (1981b, 1981d) described some of the chonetid brachiopods.

The Nalbia Sandstone marks the first appearance of the ammonoids *Paragastrioceras wandageense* and *Daubichites goochi*, which caused Cockbain (1980) to assign the unit a Roadian (late Artinskian) age.

BAKER FORMATION

Definition

The Baker Formation (Condon, 1954) is the uppermost unit of the Byro Group, and is conformably overlain by the Coolkilya Sandstone. The type section (Fig. 69) is above the main reference section of the Nalbia Sandstone, near the headwaters of Blackheart Creek at the northern end of Kennedy Range.

Lithology

The Baker Formation is a predominantly fine-grained unit deposited mainly in an offshore environment, in deeper conditions than the Nalbia Sandstone. The sequence coarsens to the southeast, reflecting shallower depths and closer proximity to the basin margin.

Condon (1967) noted that the section immediately north of Coolkilya Pool is "sandier than elsewhere" (p. 175). This may be due to infiltration of the upper, exposed layers of the Baker Formation by superficial sand, a not uncommon occurrence in soft, friable sediments throughout the Carnarvon Basin.

Distribution and thickness

Like the underlying Nalbia Sandstone, the outcrop of the Baker Formation is restricted to the Wandagee area, where it outcrops poorly, and the northern, eastern and southern margins of Kennedy Range, where locally it is moderately to well exposed. The type section as measured by Moore, Denman and Hocking (1980) is 52 m thick. The two greatest thicknesses recorded are 89 m in Kennedy Range 1 (Lehmann, 1967) and 90 m in BMR 6 Muderong (Condon, 1967). Elsewhere, Condon (1967) records 41 m immediately north of Coolkilya Pool, and thicknesses ranging from 64 to 21 m around the margins of Kennedy Range.

Fossils and age

The Baker Formation is poorly fossiliferous, with a fauna of foraminifers and chonetid brachiopods (Archbold, 1981d). It is Roadian (late Artinskian) in age because of its stratigraphic position.

KENNEDY GROUP

Stratigraphy

The Kennedy Group (Condon, 1954) is the siliciclastic, dominantly sandy sequence consisting of the Coolkilya Sandstone, Mungadan Sandstone and Binthalya Formation. Condon (1967) considered that the lower contact (with the Byro Group) was unconformable, but later work summarized in Moore, Hocking and Denman (1980) showed the contact was conformable. The upper boundary of the Kennedy Group is an eroded unconformity beneath Mesozoic and Cainozoic rocks.

Siliciclastic sediments in several wells in the northern Carnarvon Basin along the Peedamullah Shelf and southern Cape Preston Arch have previously been assigned to the Kennedy Group because of their Late Permian age. However, they are here named the Chinty Formation where there is no marked unconformity beneath the Triassic, as they appear to be related to the initial stages of Triassic sedimentation. In some wells (*e.g.* Sholl Island 1), there is an angular unconformity separating Late Permian and Triassic sediments. In such cases, the Late Permian sequence may be an age-equivalent of the outcropping Kennedy Group, but is otherwise unrelated. Lithologically, there appears to be little similarity beyond the fact that sequences in both areas are sand dominant, and the name Kennedy Group should not be extended to the northern area.

Facies description and interpretation

In their study of the Kennedy Group, Moore, Hocking and Denman (1980) recognized eight facies, which could be grouped into a fine-grained (siltstone) and a sandstone facies association. The

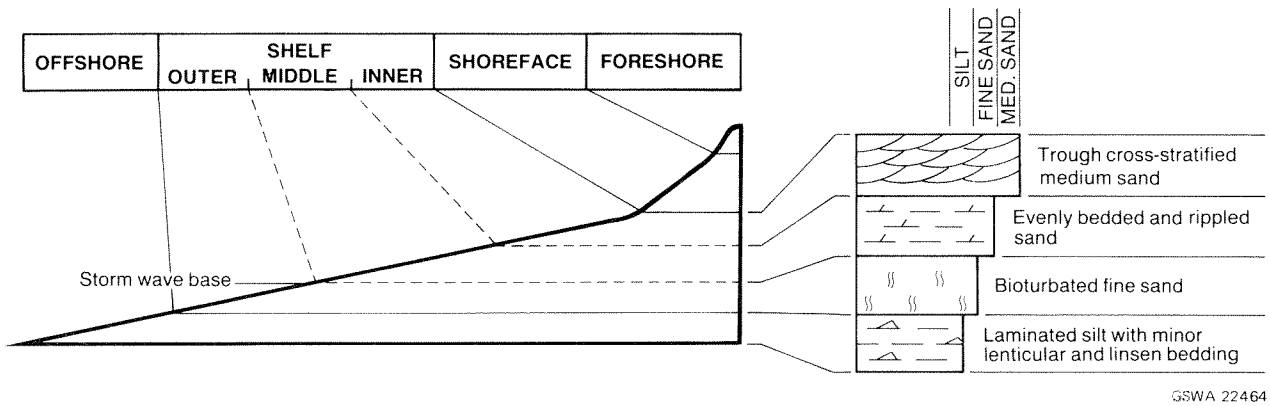

Figure 70. Depositional model showing lithofacies and interpreted environments for the Kennedy Group, excluding the lower Coolkilya Sandstone.

model is shown in Figure 70. These eight facies apply to the upper Coolkilya Sandstone, Mungadan Sandstone and Binthalya Formation. The lower Coolkilya Sandstone is best related to the facies scheme and depositional model for the Byro Group, as it is transitional between the Byro Group model and the Kennedy Group model.

Fine-grained facies association

Two major facies are recognized, a grey-siltstone facies and a lenticular to linsen-bedded facies. They are end-points between which there is a continuous gradation of lithofacies. The first facies occurs in all three formations, while the second is developed mainly in the Binthalya Formation. A very minor, coarse, sandy siltstone facies is present in the Mungadan Sandstone and Binthalya Formation.

Grey-siltstone facies: The facies consists of evenly laminated to very thinly bedded, pale-grey siltstone and sandy siltstone in units 0.5 to 4 m thick. Small curved and subvertical burrows are present. Deposition took place in quiet, reducing, marine conditions, probably in an offshore setting below wave base. There are only rare laminated sand interbeds (reasonably common in the equivalent Byro Group facies), suggesting no pronounced storm influence.

Lenticular to linsen-bedded facies: This consists of isolated ripple lenses and connected ripple trains of fine sandstone in an evenly laminated, grey-siltstone matrix. Ripples generally have an undulating base and are symmetrical or near symmetrical. The facies is bioturbated throughout, with common small curved burrows. The facies developed in a generally low-energy marine environment, probably at depths where only the deep-based waves associated with storms had an effect on the sediment. The small amounts of sand present were introduced during storms and reworked by these deep-based waves. The facies thus represents a slightly shallower environment than the grey-siltstone facies, probably with greater storm activity.

Coarse sandy-siltstone facies: This facies, although only minor, is not easily related to the Kennedy Group depositional model. It consists of very coarse-grained sandstone interbedded with, or disseminated through, shale and fine siltstone. The sandstone commonly forms thin even beds or lenses separated by centimetre thick, discontinuous bands of siltstone. The intimate association of low-energy silts with high-energy coarse sands is puzzling; Moore, Hocking and Denman (1980, p. 66) tentatively suggested that the facies formed either offshore from a distributary system, or nearshore in a protected environment near a barrier island.

Sandstone-facies association

Five facies are recognized in this association. Three represent deposition on a broad sandy, wave-dominated marine shelf, while the other two occur primarily in the lower part of the Coolkilya Sandstone and are best related to the Byro Group depositional model.

Bioturbated-sandstone facies: The facies consists of intensely bioturbated, greyish to reddish brown, poorly sorted, fine- to very fine-grained, locally silty, sandstone. A varied ichnofauna, of which *Zoophycos* is the most notable form, is present, and autochthonous coquinas are present but rare. The facies is a major component of the Coolkilya Sandstone and Binthalya Formation, and a minor component of the Mungadan Sandstone. It formed in a marine shelf below wave base, where wave and current reworking was minimal, and slow sedimentation rates allowed intense bioturbation.

Evenly bedded and ripple-laminated sandstone facies: This consists of thin intervals of evenly bedded or ripple-laminated, fine- to medium-grained sandstone. Clay-draped bedding surfaces locally contain well-preserved trails (Moore, Hocking and Denman, 1980, Figs 6G, 6H and 6I) but the facies is otherwise only weakly bioturbated. The facies is common throughout the Kennedy Group, and is best developed in the Mungadan Sandstone and Binthalya Formation. It was probably deposited above wave base in a marine-shelf environment with moderate wave and current activity. Oscillation ripples and clay drapes formed during quiet periods.

Cross-stratified sandstone facies: The facies consists of trough cross-stratified fine- to coarse-grained sandstone, with minor tabular cross-stratification. It is locally common in the Binthalya formation and occurs sporadically in the two lower formations. The facies represents migrating megaripples in a moderate- to high-energy, wave-dominated nearshore environment. Moore, Hocking and Denman (1980) placed the facies in an inner-shelf setting, but a shoreface environment grading into the inner-shelf area is equally probable, given that the facies is a traction-current deposit developed by constant wave action.

Laminated-to-burrowed sandstone facies: This facies is the same as in the Byro Group, and is very poorly developed in the Kennedy Group except in the lower Coolkilya Sandstone. Couplets are generally thinner than in the Byro Group. The facies formed near wave base in periodically agitated conditions.

Hummocky cross-stratified facies: This is also the same as in the Byro Group, and is only present in the lower Coolkilya Sandstone.

Depositional setting

Two related depositional models, each of which envisages a shoreline to the east and/or southeast were developed for the Kennedy Group by Moore, Hocking and Denman (1980). The first model applies to the lower half of the Coolkilya Sandstone, and is essentially the model developed for the Byro Group. The dominantly sandy nearshore (shoreface) deposits are separated from dominantly finer grained, silty offshore deposits by a relatively narrow transitional zone with a moderate palaeoslope. In addition, the shoreface and transition zone deposits were dominated by storm activity, with some leakage of sand to the offshore area. The black-shale facies (lower offshore environment) does not appear to be present because of lesser water depths, and there was less leakage of sand to offshore areas, probably because of decreasing storm intensity.

The second model applies to the upper half of the Coolkilya Sandstone and the Mungadan Sandstone and Binthalya Formation, and involves a broad, sandy transition zone (or shelf) separating the sandy nearshore (shoreface) area from the silty offshore area (Fig. 70). The shelf developed during deposition of the Coolkilya Sandstone, and widened during deposition of the remainder of the Kennedy Group. Most of the group was deposited on it, with varying amounts of wave and current reworking.

The development of the shelf can be related to lessened basinal subsidence in the central Carnarvon Basin. As subsidence lessened, the basin became choked, the shelf widened and the palaeoslope strike changed from approximately north-south to northeast-southwest. Some adjustment along faults took place, as there is some indication of syndepositional movement on the Kennedy Fault System during deposition of the Coolkilya and Mungadan Sandstones (see below). At a later stage in the Triassic the main stress area shifted to the northwest, and the presently defined sub-basins within the Carnarvon Basin formed.

COOLKILYA SANDSTONE

Definition

The Coolkilya Sandstone was named by Teichert (1950) and defined (as the "Coolkilya Greywacke") by Condon (1954). Hocking and others (1980) reverted to the original name. The type section (Fig. 71) is on the eastern flank of Wandagee Hill and the base of the formation is not exposed. Condon (1967) gave its thickness as 94 m, but Moore, Hocking and Denman (1980) measured 116 m. This discrepancy is explained by the fact that Moore, Hocking and Denman considered the overlying Mungadan Sandstone to be only 36 m thick, as opposed to the 44 m measured by Condon.

Because the type section of the Coolkilya Sandstone is isolated from the main outcrop area of the Kennedy Group, in Kennedy Range, Condon (1967) designated a reference section near Southern Cross Bore at the north end of the range.

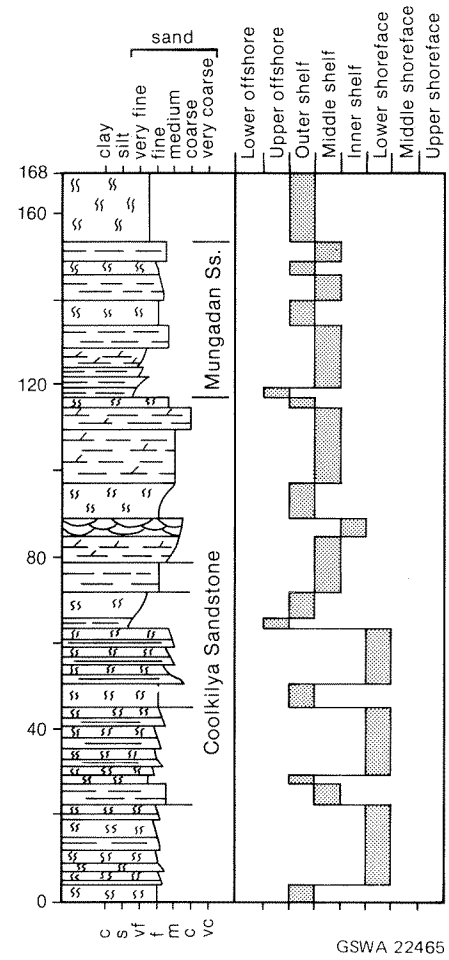

Figure 71. Type sections, Coolkilya and Mungadan Sandstones, Wandagee Hill. In the lower Coolkilya Sandstone, the outer shelf is equivalent to the transition zone.

An additional section in the eastern face of the range near Range Bore, which may be regarded as a reference section, was figured by Moore, Hocking and Denman (1980, Fig. 3).

Lithology

The Coolkilya Sandstone consists predominantly of greenish-grey to brown, fine- to very fine-grained quartz wacke. Hummocky cross-stratified and laminated-to-burrowed units dominate the lower part of the formation, while bioturbated sandstone dominates the upper part. These were deposited, respectively, in shoreface and sub-wave-base, transition-zone environments.

The lithology of the Coolkilya Sandstone at Wandagee Hill reflects greater distance from the shoreline.

Distribution and thickness

The Coolkilya Sandstone, like the rest of the Kennedy Group, is restricted to the large syncline centred on Kennedy Range and the small syncline at Wandagee Hill. Condon (1967, p. 183) mentioned small outcrops 3 km north of Wandagee Hill and in the Minilya Syncline north of the Minilya River, but these were mapped as Baker Formation by Hocking, Williams, Moore and Lavering (1983).

Along the eastern face of Kennedy Range, the Coolkilya Sandstone ranges in thickness from about 110 m to 137 m. It is markedly thicker to the west: 198 m near Southern Cross Bore (Condon, 1967) and 285 m in Kennedy Range 1 (Lehmann, 1967). At the most westerly known occurrence, in Wandagee Hill, it is unlikely to be more than 150 m thick. Some of the thickening in the Kennedy Range 1–Southern Cross Bore area can be attributed to basinward thickening, with maximum deposition in this area and less sediment escaping to the more distal area at Wandagee Hill. However, the scale of the thickening near Kennedy Range 1 suggests other factors may also apply. In the 13 km from the eastern face of the range to Kennedy Range 1, the Coolkilya Sandstone thickens from about 130 m to 285 m. The most likely explanation is that parts of the Kennedy Fault System were active during deposition of the Kennedy Group, and downwards movement of the eastern block created a trough in which greater deposition occurred.

Fossils and age

The Coolkilya Sandstone is the only formation of the Kennedy Group from which age-diagnostic fossils are known. The fauna is dominated by bivalves with gastropods, brachiopods, ammonoids, crinoids, bryozoans and foraminifers also present. The bivalves were described by Dickins (1963), and a Kungurian age for the Coolkilya Sandstone was accepted by Condon (1967) and Playford and others (1975). Cockbain (1980), in his review of Permian ammonoids from the Carnarvon Basin, utilized a different subdivision of the Permian (that of Ross and Ross, 1979) and placed the Coolkilya Sandstone in the Roadian (late Artinskian). Alternatively, the Coolkilya Sandstone is late Artinskian and Kungurian using the time scale of Harland and others (1982).

MUNGADAN SANDSTONE

Definition

The name Mungadan Sandstone was first used by Teichert (1950) and the formation as it is presently understood was defined by Condon (1954). It lies conformably between the Coolkilya Sandstone and Binthalya Formation and has its type section on the eastern flank of Wandagee Hill between the trig. station and a prominent ledge (Fig. 71). Condon (1967) gave the thickness of the type section as 44 m, whereas Moore, Hocking and Denman (1980) placed the base of the Mungadan Sandstone slightly higher than Condon and measured only 36 m.

Because the type section of the Mungadan Sandstone is isolated from the main outcrop area of the unit in Kennedy Range, the section near Range Bore (Moore, Hocking and Denman 1980, Figure 3) may be regarded as a reference section although the uppermost part of the unit is not preserved.

Lithology

The Mungadan Sandstone consists of pale-brown to cream, fine- to coarse-grained quartz arenite and quartz wacke, with minor siltstone interbeds. It is mostly even-bedded to ripple-laminated but cross-stratification is present in most exposures. Bioturbated intervals are common in exposures in the northwestern side of Kennedy Range and in Wandagee Hill. The Mungadan Sandstone was deposited mainly on a broad, sandy, wave-influenced marine shelf. Minor herringbone cross-stratification suggests weak tidal influence.

Distribution and thickness

The Mungadan Sandstone occurs in Kennedy Range and Wandagee Hill. Around the north, east and south flanks of Kennedy Range, it is generally between 40 and 50 m thick, with a minimum of 21 m near Southern Cross Bore (Condon, 1967) a maximum of 66 m at Mitta Mitta Bore (Moore, Hocking and Denman, 1980), and a slight southwards thickening overall. As with the Coolkilya Sandstone, it is noticeably thicker near Kennedy Range 1, with 95–99 m recorded in the Merlinleigh core holes (Brownhill, 1966), 93 m at Binthalya Spring (Moore, Hocking and Denman, 1980) and possibly more than 116 m in an incomplete section 4 km south of Kennedy Range 1 in the Merlinleigh Anticline. This again suggests syndepositional movement of the Kennedy Fault System in this area, as there is no apparent sedimentological reason for the thickening.

Fossils and age

Only a few bivalves are known from the Mungadan Sandstone, and the age of the unit is uncertain. Balme (*in* Jones, 1967) noted a general similarity between a microfloral assemblage in Merlinleigh 1 and one in the Upper Permian Chinty Formation from Onslow 1. However, the assemblage is actually from the Coolkilya Sandstone, not the Mungadan Sandstone as Balme stated, and the forms present could be either late Early Permian or Late Permian. In view of the macrofauna from the Coolkilya Sandstone, the first alternative is preferred, and the Mungadan Sandstone is here considered to be either Roadian or early Kazanian, because of its conformable relationship with Coolkilya Sandstone.

BINTHALYA FORMATION

Definition and thickness

The Binthalya Formation ("Binthalya Subgroup" of Condon, 1954; amended by Condon 1962a) is a sandy, silty and shaly sequence which conformably overlies the Mungadan Sandstone. The top of the unit is everywhere a post-Permian erosion surface. The type section extends east from Venny Peak on the west side of Kennedy Range and is 544 m thick (Johnstone, *in* Condon, 1967). A better exposed, but less complete, 347 m thick section is located 5 km north of the type section (Fig. 72). A well-exposed section, of which Moore, Hocking and Denman (1980) measured 193 m, is in Watermelon Creek.

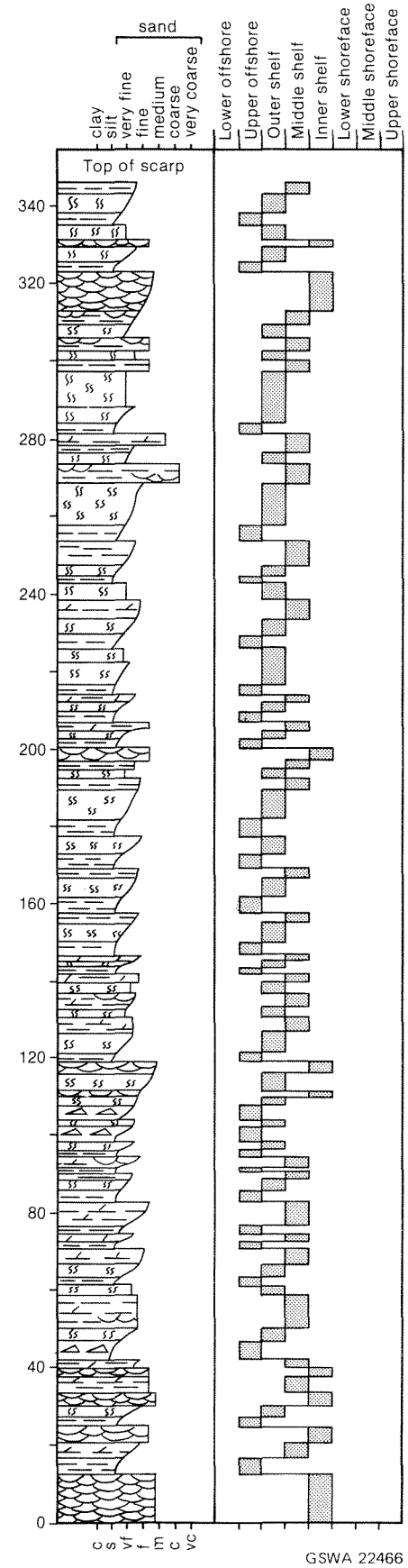

Figure 72. Binthalya Formation, 800 m south of Binthalya Spring.

Lithology and distribution

The Bindilaya Formation is present in Wandagee Hill, where it forms a fine-grained, ferrunginized, 16 m thick cap to the hill, and along the western side of Kennedy Range. In Kennedy Range, it consists of fine- to medium-grained brown sandstone and grey to black siltstone and shale. Sandstone units are evenly bedded, bioturbated, ripple laminated and locally trough cross-stratified. Deposition took place largely in a quiet, marine environment, probably on a very broad, sandy marine shelf which was below wave base most of the time. There may have been minor sediment reworking by tidal currents.

Fossils and age

The Binthalya Formation contains a varied trace fossil assemblage many of which are well organized feeding trails, but only a few body fossils. These do not appear to be age-diagnostic.

UNGROUPED UNITS

IGNEOUS AND SEDIMENTARY ROCKS IN EDEL 1

Edel 1 intersected a sequence of intercalated sediments and igneous (apparently volcanic) rocks between 354 and 2749 m (total depth). Both "Edel Formation" and "Edel Volcanics" have been used as informal names for the interlayered sequence (see Wopfner, 1981), but neither are accepted here. Potassium-argon dating of micas within the igneous intercalations gave a range in age from 241 ± 7 Ma (mid Triassic) to 260 ± 5 Ma (mid-Permian), with a general increase in age with depth (Ocean Ventures Pty Ltd, 1972). Palynological dating of a very limited section between 1469 and 1484 m (the only non-barren section) gave a Middle to Late Triassic age, from cuttings and a junk-basket sample (Balme, *in* Ocean Ventures Pty Ltd, 1972). Ocean Ventures concluded that the sediments (predominantly sandy red-beds) were distal correlatives of the Leseur Sandstone, the igneous rocks were extrusive volcanics, and the radiometric dates were slightly too old. These conclusions may not be correct, for reasons outlined below.

The presence of such a thick Mesozoic sequence offshore, with Silurian sediments at or near the surface onshore (in Dirk Hartog 17B, Tamala 1, Kalbarri 1 and the Murchison gorge) would require either a major down-to-the-west fault or pronounced subsidence and thickening, between Edel 1 and the coast. Neither is apparent on seismic lines linking Edel 1 and the coast; instead there appears to be a broad, flat, unfaulted terrace, suggesting that the clastic sequence in Edel 1 is the Tumblagooda Sandstone. Secondly, cores and cuttings in Edel 1 are very similar to the Tumblagooda Sandstone in outcrop. Thirdly, the palynological dating (as Triassic) is based on a small interval where sidewall coring failed; only cuttings and a junk-basket sample were available. All other sidewall cores were barren. These factors suggest that the igneous rocks are hypabyssal intrusives, and that the initial palaeontological dating was due to sample contamination. The overall upward decrease in age of the igneous bodies may be due to a slowly rising magmatic body which injected sills and dykes at progressively higher levels at progressively later dates.

The igneous rocks were described by Le Maitre (1975), who subdivided them into three major groups: trachytes, nosean phonolites and "lamprophyres". Details below are from his descriptions. The trachytes contain more than 60% alkali feldspar, and the main phenocrysts are sanidine, nosean, pyroxene, and hornblende. They generally show little hydrothermal alteration and commonly have a trachytic texture. The nosean phonolites contain more than 60% alkali feldspar plus feldspathoids, of which nosean is greater than 10%, and the main phenocryst types are pyroxene, hornblende, nosean, sanidine, and melanite garnet. Nepheline was not found by Le Maitre. The "lamprophyres" contain less than 60% alkali feldspar plus feldspathoids, and the main phenocryst types are pyroxene, hornblende, and biotite. Apatite and sphene are commonly abundant, and hydrothermal alteration is common. They do not have two distinct generations of ferromagnesian minerals, but Le Maitre used "lamprophyre" because he considered there were textural and mineralogical features similar to normal lamprophyres. There appear to be some gradational trends in composition through the igneous sequence as a whole, but the number of samples was insufficient for Le Maitre to confirm this.

VOLCANIC ROCKS IN ENDERBY 1

Rhyolitic rocks were penetrated by Enderby 1 in the Dampier Sub-basin between 2081 and 2149 m (total depth). The rhyolite is greenish-grey, fine grained, and contains calcite, dolomite and quartz veins. It consists of small plagioclase laths with occasional quartz crystals set in a fibrous chlorite groundmass. Xenoliths of hard greenish shale within the rhyolite were present in a core from 2146–2149 m. Minor interbeds of medium-grained, well-sorted sandstone suggest the rhyolite is volcanic in origin rather than an intrusive rock.

Early Triassic palynomorphs were found at 2087 and 2106 m, and possible Late Permian palynomorphs at 2118 m, indicating the rocks are Late Permian–Early Triassic in age.

A strong seimic reflector at this level in the Enderby–Strickland area suggests that the volcanics extend through the graben separating the Enderby Trend and Lambert Shelf.

CHAPTER 7

Upper Permian-Lower Jurassic

Triassic sediments are known from two areas in the Carnarvon Basin. A thin Lower Triassic sequence outcrops in the extreme south of the basin, south of Kalbarri, and a thicker Lower Triassic to Lower Jurassic sequence occurs in the subsurface through much of the northern Carnarvon Basin. The northern sequence is probably more than 3000 m thick, and consists of the Locker Shale, Mungaroo Formation and (locally) the Brigadier and North Rankin Formations. In places, deposition was continuous across the Permian-Triassic boundary, and an Upper Permian unit, the Chinty Formation, occurs beneath the Locker Shale. It is included here because it appears to be related to the Triassic sequence rather than the major Permian sequence of the Merlinleigh Sub-basin. The southern sequence, consisting of the Wittecarra Sandstone and Kockatea Shale, is essentially a northerly extension of the Perth Basin sequence and description here is limited to the area west of the Northampton Block.

Over most of the northern Carnarvon Basin, Triassic deposition began midway through the Early Triassic. Locally, the Chinty Formation was deposited in slightly deeper parts of the basin in the Late Permian. The base of the Triassic transgression is usually shaly, though sand bodies accumulated locally. The basal section also typically contains a carbonate horizon which is here named the Cunaloo Member of the Locker Shale. Shale deposition, with minor sands, continued until midway through the Middle Triassic when a fluvial sandy sequence, the Mungaroo Formation, rapidly replaced the marine regime. In minor areas fluvial sedimentation did not commence until midway through the Late Triassic. Near the end of the Late Triassic a marine transgressive phase because quickly established, forming the Brigadier Formation and North Rankin Formation. These persisted into the Jurassic before being displaced by claystones. In some of the few wells where this part of the section has been intersected, a carbonate phase of deposition also occurs, reflecting a depletion in clastic supply from the craton. It marks the end point of the major Triassic influx of terrestrial sediment into the basin and the beginning of the depositional style characteristic of the Jurassic.

No single well has penetrated a complete Triassic sequence but the thickness is probably more than 3000 m. Over 1200 m of Upper Triassic sediments were intersected in North Rankin 1, and in Mermaid 1 an incomplete Lower to Middle Triassic section reached 800 m. Jupiter 1, on the Exmouth Plateau, penetrated 3000 m of Upper Triassic.

The sandy Mungaroo Formation is the reservoir for the gas/condensate and oil accumulations on the Rankin Platform.

CHINTY FORMATION

Definition

The Chinty Formation (Hocking, 1985) is a sequence of sandstone, shale, siltstone and minor limestone, which underlies the Locker Shale with conformity or minor disconformity in several wells on the Peedamullah Shelf. The type section (Fig. 73) is between 2096 m and 2258 m in Onslow 1. In Onslow 1 the Chinty Formation is unconformable on the Byro Group, and in Mermaid 1 it rests on Precambrian rocks. Other wells (Hope Island 1, Cunaloo 1) have not intersected a complete sequence.

The formation was previously assigned to the Kennedy Group, largely because the only microflora in the Carnarvon Basin, which resembled that of the Chinty Formation in Onslow 1, came from the uppermost Coolkilya Sandstone in Merlinleigh 1 (Balme, *in* Jones, 1967). We do not agree with this correlation for two reasons. Firstly, the Kennedy Group is clearly related to the main late Carboniferous–Early Permian phase of sedimentation, Whereas the Chinty Formation appears to be related to the initial stages of Triassic sedimentation. Bowering (1968) and Young and Wright (1978) noted that there was no evidence of an unconformity between the Chinty Formation

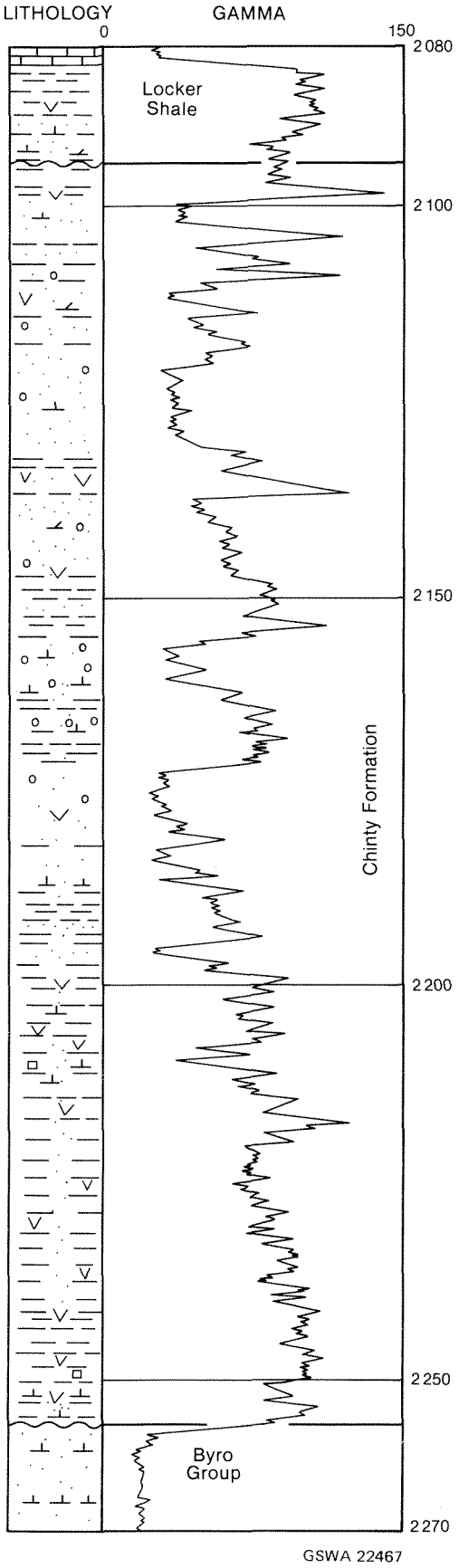

Figure 73. Gamma-ray and lithological log, Chinty Formation type section, Onslow 1, 2096–2258 m.

and the Locker Shale in Hope Island 1 and Mermaid 1, respectively, and Balme (*in* Bowering, 1968) considered that the lowermost Locker Shale in Hope Island 1 was probably Late Permian. The evidence of an unconformity in Cunaloo 1 is very meagre (Meath, 1972), although Jones (1967) considered that the contact was unconformable in Onslow 1. Secondly, the palynological dating of the Chinty Formation (Balme, *in* Jones, 1967; Balme, *in* Bowering, 1968; Wiseman and Dolby, *in* Meath, 1972) and the Kennedy Group (Balme, 1966) is not precise: while a Late Permian age is clear for the Chinty Formation from palynology and its relationship with the Locker Shale, the forms recovered from the Kennedy Group could be either Late Permian or late Early Permian. Macrofossils recovered from the Coolkilya Sandstone (the only unit of the Kennedy Group to be accurately dated) indicate that it is late Early Permian (Roadian or Kungurian) and we consider it improbable that the remainder of the Kennedy Group spans all of the Late Permian. These reasons, added to the fact that the two sequences are only broadly similar lithologically, make the erection of a new unit, the Chinty Formation, desirable for this Upper Permian sequence. Not all Upper Permian sediments on the Peedamullah Shelf and Cape Preston Arch are included in the Chinty Formation. In some wells (*e.g.* Sholl Island 1) an angular unconformity separates the Upper Permian and Triassic sequences, and the Upper Permian is tentatively correlated with, but not assigned to, the Kennedy Group.

Lithology

The Chinty Formation is dominantly sandstone with lesser siltstone, shale, and (in Hope Island 1) limestone. The sandstone is mostly light brown to grey, fine grained, variably calcareous, and commonly silty. Traces of pyrite are common, and cross-bedding can be seen in cores from Onslow 1 (Jones, 1967) and Hope Island 1 (Bowering, 1968). Both siltstones and shales are greyish in colour, and are commonly soft, carbonaceous and pyritic. Bowering (1968) noted the presence of glauconite in the interval from 1157 to 1324 m in Hope Island 1.

In Onslow 1, the sequence is dominantly sandy between 2096 and 2188 m, with some interbedded siltstone and shale and a significant silty interval between 2166 and 2171 m. Coarsening-upward cycles about 20 m thick are apparent on the gamma log. Between 2188 and 2258 m the sequence is shaly. A gradual coarsening-upward sequence into the sandstone can be seen on the electric logs.

In Cunaloo 1, four units were recognized by Meath (1972). Between 588 and 645 m, the Chinty Formation consists of sandstone with minor siltstone. Between 645 and 670 m, it is about 80% sandstone and 20% shale, with minor siltstone. Between 670 and 716 m it is sandstone, finer grained in the lower 3 m, and between 716 and 797 m (total depth) it consists of interbedded shale and sandstone with minor siltstone.

In Hope Island 1, four units were distinguished by Bowering (1968), but these do not readily correspond to those in other wells. The upper unit, between 1067 and 1121 m, is sandstone with minor siltstone. Below this, between 1121 and 1157 m, is recrystallized, bioclastic calcarenite, and below this, between 1157 and 1324 m, is interbedded siltstone and sandstone, with minor shale and thin bands of limestone. The lower unit, below 1324 m, consists of sandstone with minor siltstone and shale.

In Mermaid 1, the Chinty Formation rests on Precambrian gneiss and consists of slightly dolomitic white to light-brown sandstone, pyritic near the base. The basal 3 m is a residual lag (Young and Wright, 1978).

Distribution and thickness

The Chinty Formation has been recognized in Onslow 1 (2096–2258 m), Hope Island 1 (1067–1426 m, total depth), Cunaloo 1 (588–797 m, total depth), and Mermaid 1 (1230–1259 m). Wells to the south, east and northeast intersected older sediments beneath the Cretaceous, while wells to the north and west did not reach the stratigraphic level of the Chinty Formation. The unit is expected to have a similar distribution to the Locker Shale, although this cannot be verified from the sparse available data. The section in Mermaid 1 is clearly very close to the margin of the depositional basin.

Similar sediments are present in several petroleum-exploration wells in the portion of the northern North West Shelf which lies north of the Kimberley Block (Hyland Bay Formation).

Environment and deposition

The Chinty Formation formed in a slightly deeper part of the Carnarvon Basin at a time when the remainder of the basin to the south was emergent and subject to erosion. The unit formed in large part on a sandy marine shelf with localized concentrations of skeletal carbonate debris in banks and shoals. This setting is indicated by the dominantly sandy nature of the unit, the presence of glauconite, the relatively abundant microfauna and microflora, and the limestone found in Hope Island 1. The variable thickness and lithology of the unit indicate that rates of deposition and subsidence were quite variable in different areas. Jones (1967) suggested that much of the sandy upper part of the Chinty Formation in Onslow 1 was a continental deposit which, allied with the much greater thickness intersected by Hope Island 1, suggests that the basin deepend westwards (?northwestwards) and had a shoreline close to Onslow 1.

Fossils and age

The age of the Chinty Formation is well established as Late Permian, from palynological studies by Balme (*in* Jones, 1967; and *in* Bowering, 1968) and Wiseman and Dolby (*in* Meath, 1972). Williams (*in* Young and Wright (1978) assigned the microflora to palynostratigraphic unit VII of Balme (*in* Kemp and others, 1977). It is not known if the formation extends into the Triassic.

LOCKER SHALE

Definition

The Locker Shale was named and defined by Parry (*in* Jones, 1967), and was first published by Balme (1969). It is a dominantly argillaceous, marine sequence of Early and Middle Triassic age and is nowhere exposed. The type section (Fig. 74) is the interval between 1587 and 2096 m in Onslow 1. In this section, the Locker Shale rests, probably unconformably, on the Upper Permian Chinty Formation, and is overlain conformably by the Mungaroo Formation. In other wells (Cunaloo 1, Hope Island 1, Mermaid 1) there is little or no evidence of an unconformity between the Locker Shale and the Chinty Formation.

The Cunaloo Member is a carbonate horizon which occurs near the base of the Locker Shale in most areas.

Cunaloo Member

The Cunaloo Member (Hocking, 1985) is a carbonate interval, with minor argillaceous beds, near the base of the Locker shale. The type section is the interval between 534 and 549 m in Cunaloo 1. The top and bottom of the unit are usually abrupt but locally a transitional zone occurs, as for example the thin limestones below the main body in Cunaloo 1 (Fig. 75A).

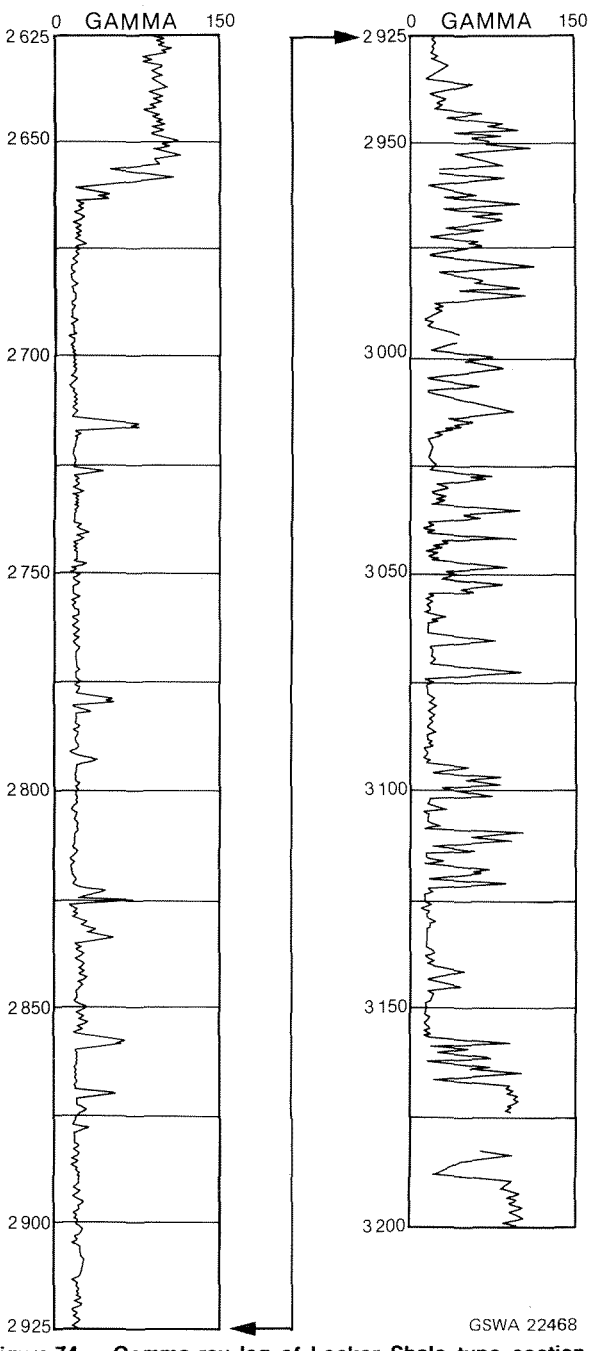

Figure 74. Gamma-ray log of Locker Shale type section, Onslow 1, 1587–2096 m.

The limestone is dominantly a white, pale-brown or grey, pelitic lime mudstone, locally recrystallized to fine spar, and isolated dolomite rhombs occur. Rarely, the lime mud has been winnowed away resulting in a grainstone. Very fine quartz sand grains occur, and locally are abundant enough to form a calcareous siltstone. In these, there are similar-sized green glauconite pellets and occasionally an unidentified black mineral. Towards the base of the member, pyritic black shale is interbedded with the limestone. The limestone is usually fossiliferous, locally a packstone, with ostracods and small bivalves the most common forms.

The Cunaloo Member extends from the Exmouth Gulf area north to Enderby 1. The thickest section is in Fortescue 1 where more than 18 m of limestone is present and the thinnest, Hope Island 1, where only 4.5 m is present.

The Cunaloo Member is a clear-water marine deposit which formed in a quiet, well-aerated environment, with local reducing conditions.

Lithology

The Locker Shale is generally a uniform shale sequence, with abruptly bounded, local sandy horizons and, near the base, the carbonate Cunaloo Member. The shale is grey except when lignitic (brown) or glauconitic (green). It is commonly silty, micaceous and feldspathic. Disseminated pyrite is usually present, and pyrite stringers occur in places.

The sandstone interbeds are discontinuous and dominantly very fine to fine grained, with an overall range in grain size from silt to conglomerate. They are commonly glauconitic.

Distribution and thickness

The Locker Shale has only been intersected near the basin margin, although it has been traced as far west as the Exmouth Plateau on seismic sections (Wright and Wheatley, 1979). From the preserved thicknesses in the most easterly well intersections, the shale was probably deposited as far east as the present-day eastern margin of the basin. Triassic sediments are not known in the Gascoyne or Merlinleigh Sub-basins (except south of Kalbarri). The coeval marine Kockatea Shale in the Perth Basin is assumed to have been connected to the open sea, via a northwesterly extension of the Abrolhos Sub-basin (Perth Basin), which linked up with a southwesterly extension of the Exmouth Sub-basin.

A full section of the Locker Shale has only been found in a few wells. The type section is 509 m thick, compared with approximately 350 m in Hampton 1 and Enderby 1, and nearly 1000 m in Flinders Shoal 1. The section in the Hampton/Enderby area may be condensed, and it covers a greater time span than the Onslow 1 section but is only two thirds as thick. The Flinders Shoal area may have been a sand-bypass region because shale deposition continued much longer there, into the Late Triassic (Norian).

Fossils and age

Macrofossils are rare in the Locker Shale, but a rich assemblage of pollen, spores and microplankton is present (Balme, 1969; Dolby and

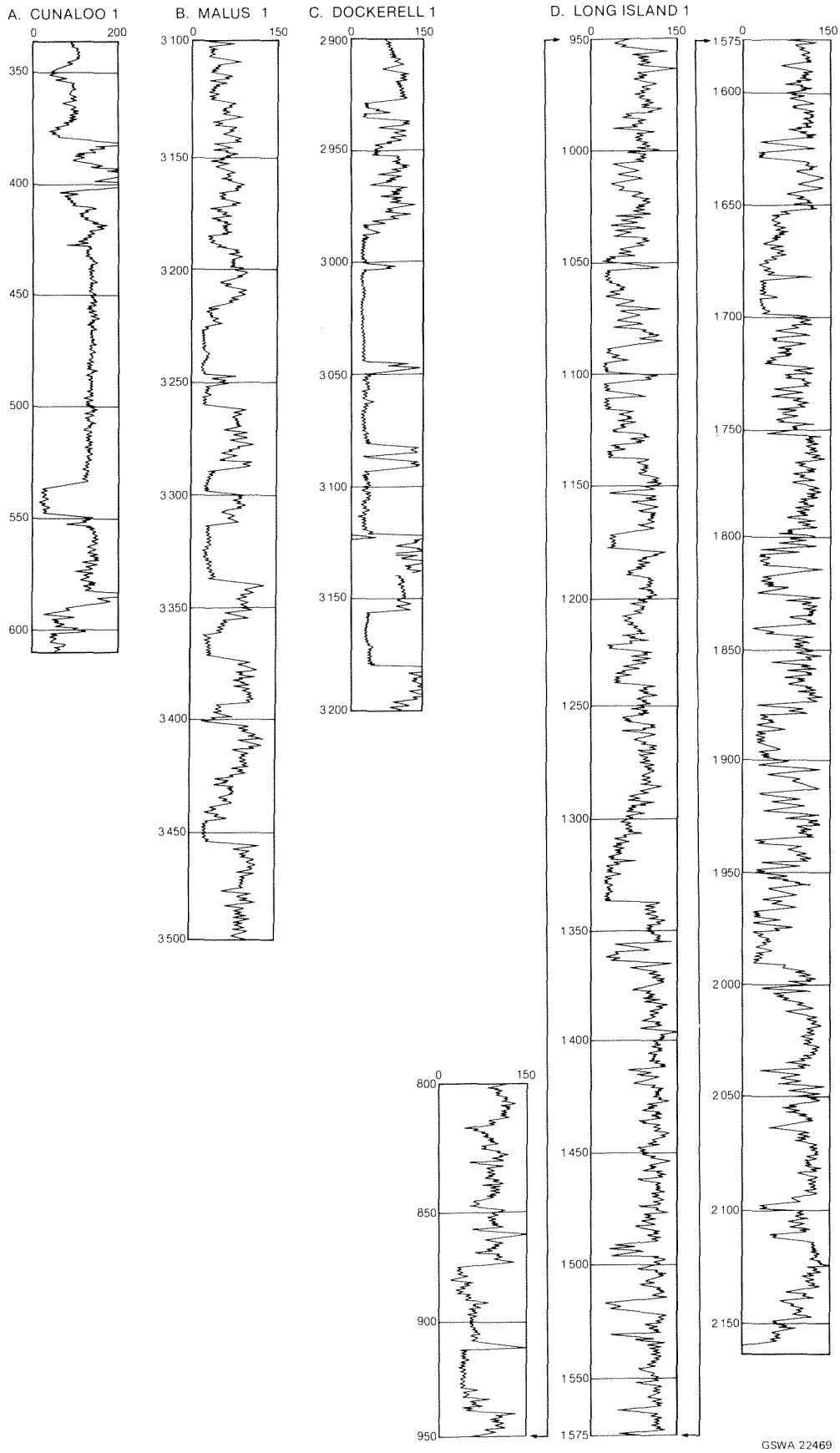

Figure 75. Gamma-ray logs of Triassic sediments. A. Locker Shale in Cunaloo 1, showing uniform shale lithology except for high gamma-ray beds near the base and the abrupt limestone of the Cunaloo Member (534–549 m). B. Part of Mungaroo Formation section from Malus 1, showing fining-upward point-bar units. C. Part of Mungaroo Formation section from Dockrell 1, showing massive sand units probably deposited in braided-fluvial environment. D. Type section of Mungaroo Formation, Long Island 1. In lower part of section, sandy marine basal beds are succeeded by fluvial sands which are in turn succeeded by marine interdistributary sediments.

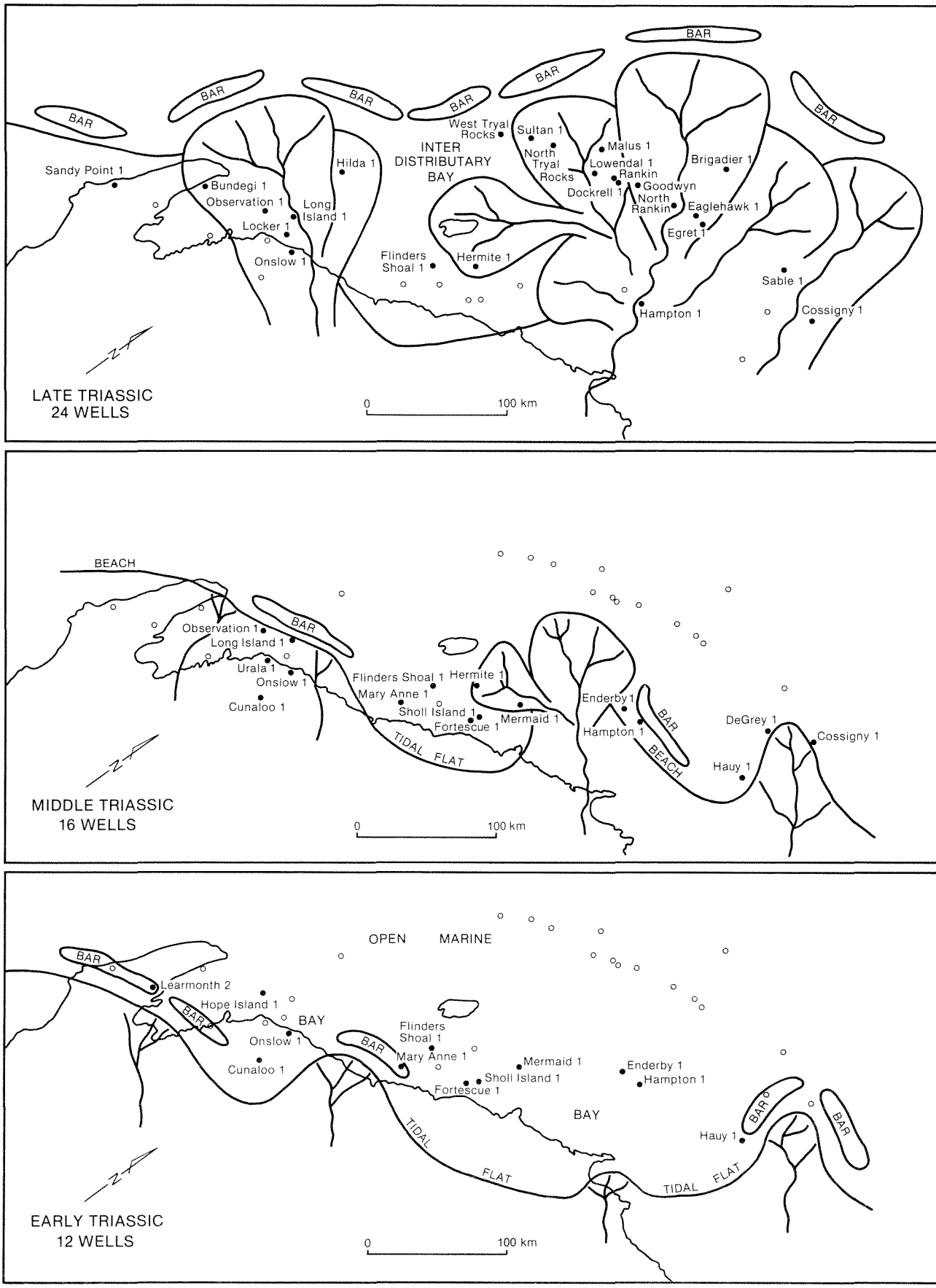

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Figure 76. Postulated Triassic palaeogeography, with control wells for each time interval. Lower Triassic deposition was open-marine shale or limestone with some paralic sand near river mouths. In the Middle Triassic, the coastline prograded northwestwards with deltas providing more coarse clastic sediment. Progradation continued in the Upper Triassic but interdistributary bays were left between major river systems. Abundant sands accumulated as extensive beach deposits.

Balme, 1976), and conodonts occur in some wells (*e.g.* Sholl Island 1). Over most of the northern Carnarvon Basin, deposition of the Locker Shale began in the Smithian (Late Scythian), although locally deposition appears to have been continuous from the Late Permian (Balme, *in* Bowering, 1968). Significant influx of sandy sediment (the Mungaroo Formation) began in most areas in the Anisian, although it locally took place as early as the Spathian (Mermaid 1) or as late as the Norian (Flinders Shoal 1).

Environment of deposition

The presence of marine fossils and glauconite indicates that the Locker Shale is a marine deposit. The paucity of the flora, fauna and local abundance of pyrite suggest restricted circulation. Deposition began in the wake of a transgression which progressively covered an area of generally low relief, with local seaways where deposition was continuous from the Permian. Sea-floor conditions were quiet and relatively inhospitable, resulting in a fauna of low diversity and abundance. Sand horizons may have been brought into the basin by turbidites, which could also transport wood, spores, and pollen from nearshore areas without appreciably increasing the overall sand content of the Locker Shale.

During the initial transgression enough coarse terrigenous material was available to form a basal sand in some parts of the basin (Hope Island 1, Mary Anne 1, Hauy 1) but elsewhere shale was deposited. When this initial sand supply was exhausted, the basin became sediment starved and carbonate deposition became important, with widespread deposition of the Cunaloo Member. However, as fluvial systems were re-established, clastic material was again introduced into the basin and a thick sequence of shale formed (Fig. 76).

MUNGAROO FORMATION

Definition

The Mungaroo Formation ("Mungaroo Beds" of Parry, *in* Jones, 1967; amended by Playford and others, 1975) is the sandy sequence which confomably overlies the Locker Shale and is overlain conformably by the Brigadier Formation, or by the Dingo Claystone (generally conformably but locally with an angular unconformity). The type section (Fig. 75D) is in Long Island 1 between 749 and 1992 m, but the best known sequence is in North Rankin 5, between 2679 and 3500 m (total depth).

Parry (*in* Jones, 1967) proposed the Mungaroo Formation because of its consistent sand abundance compared to the Locker Shale. The transition between the two units is commonly gradational, as in the type section, where the underlying Locker Shale is not a uniform shale sequence but has abundant thin sand beds. The base of the Mungaroo Formation was placed at the base of the first thick sand, rather than at the base of the first sand interval, which is at greater depth.

The Mungaroo Formation is very variable (Fig. 75B, C, D) and it may be possible in future to divide it further than was suggested by Crostella and Barter (1980), who proposed that the Rhaetian-Pleinsbachian (Latest Triassic–Early Jurassic) interval should be divided into the "Brigadier Beds" and "North Rankin Beds". These units are recognized herein.

Lithology

The Mungaroo Formation is a siliciclastic sequence which, although notably sandier than the Locker Shale, is still dominantly argillaceous. Parts of the section are very sandy, but only in limited areas. For example, the Rhaetian to Lower Hettangian (uppermost) portion of the Mungaroo Formation ranges from 80% sand in the North Rankin area to 10–20% further south (Crostella and Barter, 1980). Simple estimates from gamma-ray logs suggest overall sand contents of 25 to 40% in most wells.

Two major fine-grained facies are present, brown claystone and grey claystone. These can be attributed to three environments. Brownish to reddish oxidized claystones are fluvial overbank deposits. Reducing conditions were locally present in the fluvial environment, such as in deep abandoned channels, and dark-grey bioturbated shales formed therein. Thin coal layers occur, and locally are an important constituent (*e.g.* Tidepole 1, 3100–3175 m). Grey bioturbated claystone is also associated with marine deposits, and probably formed in lagoonal and interdistributary bay environments.

A wide range of sandstone facies is present, from thin, generally finer grained beds within thick shaly sequences (formed by lagoon washovers or fluvial levees) to thick fluvial channel sands which are mostly medium-grained but range from fine-grained to granule size (Fig. 75B, C). Lag conglomerates with clasts several centimetres in diameter occur at the base of some of the

fluvial intervals. Sideritic concretions, calcite cement and glauconite occur in marine sandstone, and pyritic concretions and siliceous cement in fluvial sandstone.

The sandstones are quartzose, with uncommon feldspar and lithic clasts. Grain size and maturity vary with the depositional environment, but there is a mineralogical uniformity throughout the formation, suggesting a single provenance. In thin section, many of the quartz grains show some undulose extinction, and some grains contain inclusions. Microcline is the most common feldspar, with lesser orthoclase, albite and perthite. Lithic grains are mostly red chert, but quartzite and shale are also present. Accessory minerals include mica, tourmaline and zircon. Most grains are subrounded.

Distribution and thickness

The Mungaroo Formation is known only in the subsurface. Although it was probably deposited near the present-day eastern margin of the Carnarvon Basin, it is now only preserved in more basinal areas. The unit has been encountered in the Flinders Fault area (where it was originally defined) and the Rankin Platform, and is assumed to be present at depth between these areas. Possible correlatives of the Mungaroo Formation extend to the Exmouth Plateau.

On the Rankin Platform the base of the Mungaroo Formation has not been reached, while in the Flinders Fault area the top has been eroded. The deposited thickness of the Mungaroo Formation is thus difficult to ascertain. The type section is 1198 m thick, with an eroded top; Rankin 1 encountered 1247 m with the top eroded and without reaching the base of the Mungaroo Formation; and Jupiter 1 on the Exmouth Plateau encountered over 3000 m of sediments which correlate with the Mungaroo Formation (Vos and McHattie, 1981).

Detailed correlation is difficult except in small areas (*e.g.* Goodwyn Field, North Rankin Field). Seismic sections show that only a few beds, such as the coal measures and carbonate horizons of Crostella and Barter (1980), have a wide extent.

Fossils and age

A varied and abundant assemblage of spores and pollen grains is present in the Mungaroo Formation, and Balme (1969) and Dolby and Balme (1976) discussed the palynology and age of the unit in general terms. In most areas deposition of the Mungaroo Formation started in the latest Scythian to earliest Anisian (Crostella and Barter, 1980), but locally it was as late as the Norian (Flinders Shoal 1). Deposition of the Mungaroo Formation finished in the Dampier Sub-basin and Rankin Platform area in the Norian-Rhaetian, but it appears to have continued as late as the Toarcian (Jurassic) in parts of the Exmouth Sub-basin, based on gross lithological trends.

Environment of deposition

Sediments belonging to the Mungaroo Formation form part of a clastic depositional cycle with progradation into a marine environment followed by transgression. Initially it was believed that the sediments were derived from the northwest (Kaye and others, 1972), but later dipmeter interpretation indicated an easterly or westerly derivation, with an eastwards provenance finally gaining acceptance (Powell, 1976b; Harris, 1978).

The type section in Long Island 1 (Fig. 75D) was deposited near the Flinders Shoal Embayment (Fig. 76), a depressed area with few coarse-grained clastics, and the Mungaroo Formation was dominated by marine processes. Below approximately 1830 m, the section consists of coarsening-upward cycles, in places stacked into 30 m sand packages, which may be beach/nearshore bar deposits. Between about 1620 and 1830 m the sequence is fluvial-dominated and characterized by sandy, sharp-based, fining-upward cycles. In the lower portion of this interval, the cycles may be formed in part by tidal-point bar migration in an estuarine setting. At about 1620 m the delta was abandoned in this area and a 280 m thick sequence of interdistributary clays, with some crevasse splays, was deposited. The delta then switched back to the Long Island area, and fluvial sediments were deposited between 870 and 1340 m, after which marine conditions returned.

The Mungaroo Formation in the North Rankin area was described in some detail by Crostella and Barter (1980). Three cycles of fluvial deposition took place. The first is more than 1500 m thick, the second a maximum of 600 m, and the third, less than 250 m thick. The cycles begin with braided-fluvial deposition with the development of coal measures. A widespread marine transgression interrupted the third cycle, resulting in the lagoonal to marine deposition of the Brigadier Formation.

Cook and others (1985) briefly outlined the depositional setting of the Mungaroo Formation on the Exmouth Plateau, and considered that it was a deltaic complex.

Economic aspects

The Mungaroo Formation is the reservoir for the giant gas accumulations of the Rankin Platform. Although the formation is typified by persistent sand beds, the sand percentage is variable, and significantly affects the economic viability of hydrocarbon accumulations. For example, Haycock 1 is non-commercial even with a 127 m hydrocarbon column because the sand content is only 19%. Porosity and permeability are good (Crostella and Barter, 1980), which is important given the water depths and isolation of the Rankin Platform and Exmouth Plateau. Descriptions of the reservoir parameters are given in the section on hydrocarbon potential (Chapter 13).

BRIGADIER FORMATION

Definition

The Brigadier Formation is a dominantly fine-grained sequence which conformably overlies the Mungaroo Formation in the Dampier Sub-basin, and may extend into the southwestern Barrow and Exmouth Sub-basins. It is conformably overlain by the North Rankin Formation, where present. Elsewhere, it is overlain by the Dingo Claystone. Generally, the contact is conformable in the deepest parts of the basins, and progressively more unconformable towards sub-basin margins.

The unit was initially proposed, as the "Brigadier Beds", by Crostella and Barter (1980), but they did not formally define it because of the lack of publicly available data. The name was formalized by Hocking (1985), despite a continued lack of information, in order to establish a stratigraphic framework for future workers. The type section is the interval between 3612 and 3964 m in Brigadier 1, as suggested by Crostella and Barter.

Lithology

Crostella and Barter (1980, p. 29) described the Brigadier Formation as very thinly interbedded sandstone and claystone, with several, possibly lenticular, intervals of fine- to medium-grained sandstone. In the uppermost part of the unit, claystone is dominant, with minor siltstone.

Probable extensions of the Brigadier Formation in the Barrow and Exmouth Sub-basins consist of quartz siltstone with lesser shale and claystone, and minor sandstone. The sandstone is fine-grained, quartzose, and occurs as thin interbeds. They are underlain by, and appear to be gradational from, relatively thick and continuous sandstone sequences assigned to the Mungaroo Formation.

Distribution and thickness

Crostella and Barter (1980, Fig. 7) considered the Brigadier Formation in the Dampier Sub-basin, easternmost Barrow Sub-basin and Rankin Platform. They showed the southeastward limit of the depositional basin as running approximately from Hermite 1 to Sable 1. These two wells lay at the seaward edge of a paralic depositional zone, and bathymetry deepened to the northwest. Fourteen wells intersected the formation.

Extension of the Brigadier Formation to the Exmouth Sub-basin is based on the presence of a fine-grained sequence in the same stratigraphic position as in the Dampier Sub-basin, above the thick sandstone-dominated sequence of the Mungaroo Formation and below the Dingo Claystone (which commonly has a basal calcareous interval). Probable intersections are in Sandy Point 1 (1926–2359 m) and Yardie East 1 (4911–5182 m, drilled depth). It is not clearly developed in Hermite 1 (although shown by Crostella and Barter) and is absent in Bundegi 1 and Murat 1. Recognition of the unit is difficult because the Lower Jurassic–uppermost Triassic section is commonly either eroded (as on parts of the Rankin Platform) or at great depth (as below Barrow Island).

Fossils and age

In the Dampier Sub-basin and Rankin Platform, the Brigadier Formation is Rhaetian to Early Hettangian in age (Crostella and Barter, 1980, p. 28-29 and Fig. 17).

Intersections in the Exmouth and Barrow Sub-basins appear to be younger. The top of the underlying Mungaroo Formation is as young as Toarcian (Bundegi 1), and the top of the Brigadier Formation ranges from Toarcian to early Bajocian. The base of the unit ranges from undifferentiated Lower Jurassic to ?early Rhaetian. Palynological assemblages generally indicate a nearshore to paralic environment.

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Environment of deposition

The Brigadier Formation is a paralic to shallow-marine deposit, formed by drowning of the Mungaroo Formation deltaic environment. Much of the formation was deposited in coastal lagoons. Crostella and Barter recognized increasing marine influence, upward through the formation, and suggested that deposition of the unit may have been stopped by a eustatic regression.

The sediments assigned to the Brigadier Formation in the Exmouth Sub-basin are coeval with the Mungaroo Formation, in nearby wells. This suggests that the Brigadier Formation, as recognized in the Exmouth Sub-basin, formed interdistributary areas between and marginally offshore from prograding lobes of Mungaroo Formation. Based on the few intersections, the formation youngs to the south, suggesting that deposition was terminated by a slow and gradual transgression. The North Rankin Formation is either absent or has been assigned to the Learmonth Formation. The overlying sediments are the deeper marine Dingo Claystone, and appear similar to the Sinemurian-Pleinsbachian sediments described by Crostella and Barter (1980, p. 30).

NORTH RANKIN FORMATION

Definition

The North Rankin Formation is a sandstone-dominated unit which rests conformably on the Brigadier Formation in several wells in the Dampier Sub-basin, Rankin Platform, and eastern Barrow Sub-basin. It is overlain by the Dingo Claystone, possibly unconformably. The North Rankin Formation was proposed by Crostella and Barter (1980, p. 29) but not formally defined because of a lack of publicly available information. Hocking (1985) formalized the name in order to expand the stratigraphic framework for future workers. The type section, proposed by Crostella and Barter, is in North Rankin 3 between 3044 and 3156 m.

Lithology

Crostella and Barter (1980, p. 29) stated that the North Rankin Formation typically comprises "fine to medium-grained sandstones with good reservoir potential. Characteristic log shapes suggest that discrete sandstone bodies become coarser upwards in a manner consistent with barrier bar or beach deposits." The sandstone is quartzose, very light grey to light olive-grey, variably silty and clayey, and contains trace quantities of pyrite. Claystone and siltstone interbeds are present near the base of the formation.

Distribution and thickness

Crostella and Barter (1980, Fig. 9) showed the facies distribution of the North Rankin Formation in the Dampier Sub-basin area. Although they showed it extending to Hermite 1, it is not clearly delineated on logs. It is absent in Anchor 1 and wells in the Exmouth Sub-basin.

The North Rankin Formation is a relatively thin unit, with thicknesses of 112 m in the type section and 53 m in Brigadier 1. Regionally, it appears to thin to the northwest.

Fossils and age

Crostella and Barter described the North Rankin Formation as late Hettangian–Sinemurian. In Brigadier 1 and North Rankin 3 it appears to be largely Sinemurian.

Environment of deposition

Crostella and Barter considered that the North Rankin Formation is a regressive sequence, deposited possibly as barrier-bar/beach deposits over the lagoonal to nearshore-marine Brigadier Formation. Marine influences are indicated by small percentages of microplankton. Detailed conclusions regarding the depositional environment cannot be reached from the information available.

WITTECARRA SANDSTONE

Definition

The name "Wittecarra Sandstone" was introduced by Johnstone and Playford (1955, unpublished) but Johnstone and Playford (*in* McWhae and others, 1958) proposed an amended "Wittecarra Formation", which also included the Kockatea Shale and Birdrong Sandstone south of Kalbarri. This was abandoned by Playford and others (1975), who returned to the original usage. The Wittecarra Sandstone is a sequence of sandstone, pebbly sandstone and claystone which unconformably overlies the Tumblagooda Sandstone in the coastal gorges south of Kalbarri. The contact with the overlying Kockatea Shale is sharp, but there is no indication that it is unconformable. The 8 m thick type section is located on the central spur at Nancy Beach (Shell House), and is shown in the middle section in Figure 77.

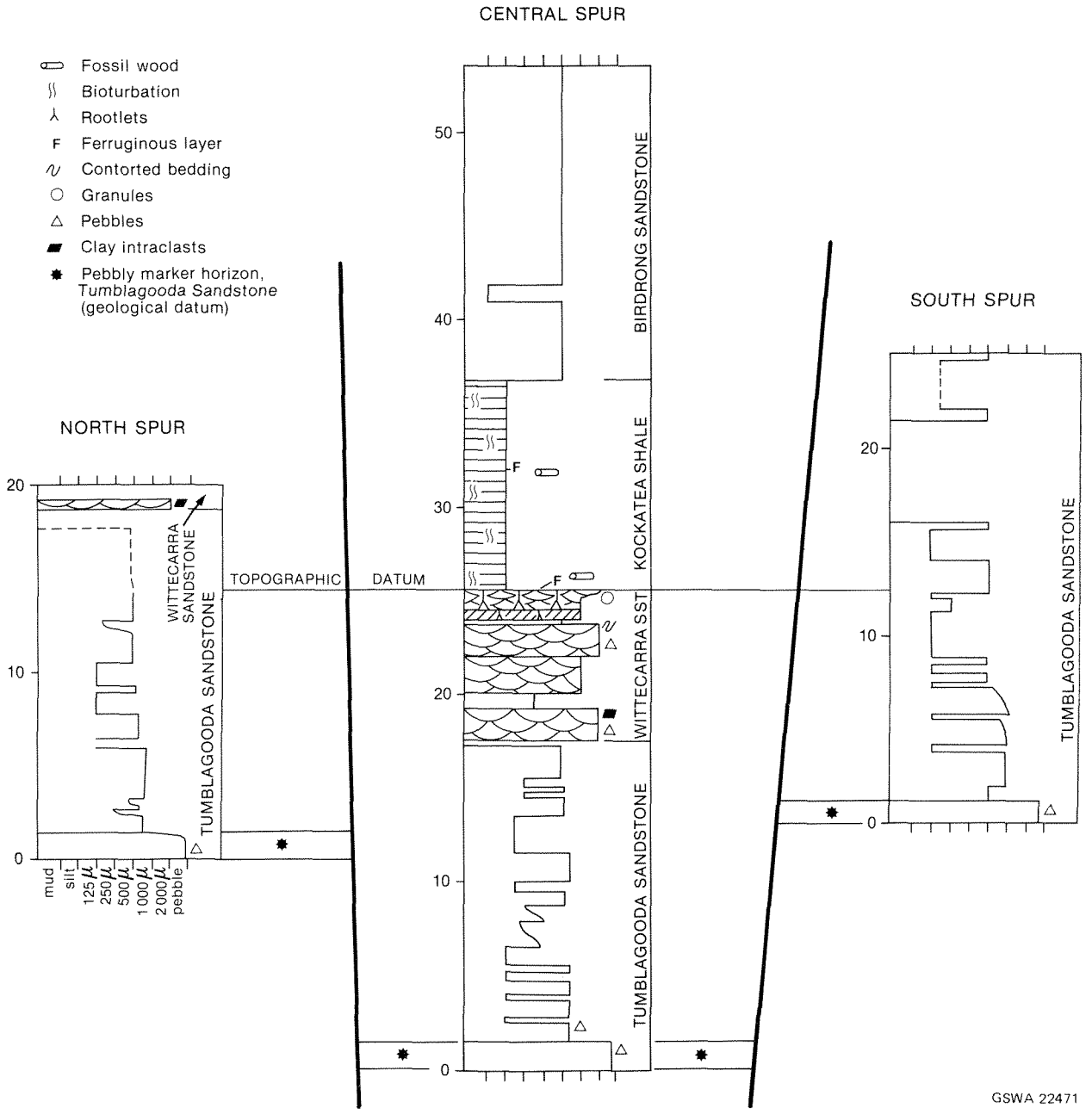

Figure 77. Measured sections of Triassic sediments at Nancy Beach, south of Kalbarri. Central spur, containing Wittecarra Sandstone type section, is small downfaulted graben.

Lithology

Clayey to silty sandstone and pebbly sandstone to conglomerate are present in almost equal amounts with lesser siltstone. The base of the unit is generally a pebbly sandstone to pebble conglomerate 1 to 2 m thick (Fig. 78). A high proportion of the clasts are claystone intraclasts, probably derived partly from adjacent low-energy areas and partly from underlying deeply weathered material. The remainder of the clasts are predominantly resistant siliceous rock types such as milky quartz, chert and jasper. These were undoubtedly derived in part from the Tumblagooda Sandstone. The matrix consists of poorly sorted quartz and lithic wacke. Bedding is outlined only by clast imbrication.

Overlying the conglomerate is a sequence of sandstone and siltstone. The siltstone is generally clayey and featureless, with only vague traces of bedding preserved. The sandstone is poorly sorted, fine to coarse grained and trough or planar cross-bedded. It is commonly silty and clayey and contains scattered pebbles and granules; it is difficult to distinguish from the Tumblagooda Sandstone. Plant rootlets (which could be mistaken for

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Figure 78. Wittecarra Sandstone south of Kalbarri. Intraclast conglomerate, with mixture of quartz pebble and reworked claystone/siltstone clasts.

Skolithos) are present in the sandstone in the top 2 m of the type section. Palaeocurrent data indicate that currents were westwards to northwards.

The Wittecarra Sandstone coarsens upwards to pebbly sandstone or conglomerate in the topmost metre of section at most localities.

Distribution and thickness

The Wittecarra Sandstone is only recognized in the coastal gorges of south Kalbarri, where both it and the Kockatea Shale are discontinuously present between the Tumblagooda Sandstone and Birdrong Sandstone. The eastwards extent of the unit is unknown because it is covered by younger sediments. Other sands at the base of the Kockatea Shale in the Perth Basin may correlate with the Wittecarra Sandstone.

The Wittecarra Sandstone is less than 10 m thick in the few localities in which it has been found, and commonly less than 5 m thick. Remeasuring and reinterpretation of the type section revealed only 8 m, rather than the 12.5 m cited by Hocking, van de Graaff and others (1983).

The distribution is at least partly fault-controlled, rather than being related to topographic irregularities in the underlying surface, as previous workers have suggested. At the type locality, detailed correlation within the underlying Tumblagooda Sandstone shows that the Triassic sequence infills a small graben of post-Triassic, pre-Cretaceous age (Fig. 77), and a fault plane and fault breccia can be seen in the northern gully. Fault control of the Triassic sequence has not been confirmed elsewhere in the coastal gorges, as outcrop is poor and access is commonly difficult.

Fossils and age

No fossils have been found in the Wittecarra Sandstone. Because of the apparently conformable relationship between the sandstone and the Kockatea Shale, it is assumed to be of Early Triassic age.

Environment of deposition

The claystone-intraclast conglomerates, poor sorting, lack of fossils (other than rootlets) and range of lithofacies in the Wittecarra Sandstone suggest that it is probably a meandering fluvial deposit. The siltstone and sandy siltstone are probably overbank deposits. The conglomerates are channel-base deposits and the sandstones are the main channel fill. The plant rootlets near the top of the formation and the presence of the marine Kockatea Shale above suggest that the river system may have been located in a marshy, coastal setting in the area of outcrop.

KOCKATEA SHALE

Definition

The Kockatea Shale (Playford and Willmott, *in* McWhae and others, 1958) extends through much of the northern Perth Basin. The type sec-

tion, 12.5 m thick, is located near the junction of Kockatea Creek and the Greenough River on GERALDTON (Playford and others, 1976). It is a shaly and silty unit with an unconformable lower contact, except where the Wittecarra Sandstone is present. West of the Northampton Block it is unconformably overlain by younger units. The northernmost outcrops are in isolated mesas and breakaways west of the Northampton Block, south of Kalbarri (in the southernmost Carnarvon Basin) and the description and interpretation which follow are restricted to this area. This sequence was called the "Minchin Siltstone" by Johnstone and Playford (*in* McWhae and others, 1958) but the name was abandoned by Playford and others (1975).

Lithology

West of the Northampton Block, the Kockatea Shale consists predominantly of white-weathered clayey siltstone to claystone, with minor intercalations of coarse-grained siltstone to fine-grained sandstone.

The white siltstone is thinly bedded to laminated, where bedding can be seen, with rippled intervals developed locally. Thin ferruginized layers (possibly beds which were originally calcareous) within the siltstone are common. At Sugarloaf Hill, trails, burrows, and various tool markings are outlined on bedding planes, and large undulose asymmetric ripples are present (Fig. 79).

The coarse siltstone and sandstone are rippled, with mainly current forms, and appear to form discrete, sharp-based interbeds. The form of the ripples suggests turbulent westwards-flowing currents. Sandstone beds are mostly less than 0.5 m thick, and persist laterally for more than 10 m, but do thicken and thin over that distance. Small, steep-sided, sandstone-filled channels are also present.

Distribution and thickness

West of the Northampton Block, the Kockatea Shale is 30 to 40 m thick and shows little variation in thickness. The section in Sugarloaf Hill is 30 m thick (Johnstone and Playford, 1955). At the Wittecarra Sandstone type locality, pre-Cretaceous erosion has removed all but 11 m of the Kockatea Shale.

Fossils and age

The Kockatea Shale is only sparsely fossiliferous, but a varied flora and fauna are known. This was listed by Playford and others (1976). Ammonoids from the Mount Minchin–Sugarloaf Hill area were described by Edgell (1964) and Skwarko and Kummel (1974). At the Wittecarra Sandstone type locality, ferruginized wood imprints are common in a ferruginized layer in the middle of the Kockatea Shale. Conchostracans from this area were described by Cockbain (1974).

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Figure 79. Kockatea Shale, Sugarloaf. Flutes, grooves and tool markings on underside of ferruginized bedding plane. Note small ammonoid impression below coin. Coin is 23 mm in diameter.

The ammonoids indicate that the formation is of Early Triassic age, and that the base is time transgressive (Playford and others, 1976).

Environment of deposition

The laminated siltstone which dominates the Kockatea Shale, together with sparse marine fossils, indicate that the formation was deposited in a quiet offshore-marine environment, below wave base. Facies do not change markedly over the area of outcrop west of the Northampton Block on GERALDTON, indicating that the environment was laterally persistent. Sand bodies within the Kockatea Shale may be distal turbidite deposits. This is suggested by their abrupt bounding surfaces, current bedding and westwards palaeocurrents. The alternative, that they are non-turbiditic distal prodelta sands, is less likely because there is no known evidence of deltaic deposition in the Kockatea Shale upslope to the east (Playford and others, 1976).

In the coastal gorges on AJANA, an offshore environment is less certain because of the apparently conformable relationship between the Kockatea Shale and the fluvial Wittecarra Sandstone. This area was proably closer to the margin of the basin, and deposition may have been in a near-shore low-energy environment or a brackish, coastal environment. This is supported by the known fauna (Cockbain, 1974), the presence of fossil wood in ferruginized layers and the lack of sandstone intercalations.

CHAPTER 8

Jurassic

Major tectonism occurred during the Jurassic, and the structural elements which define the sub-basins of the Carnarvon Basin developed primarily at this time. Faulting took place in an extensional regime around the western edge of the Australian craton, and fault-bounded basins developed which rapidly filled. The Gascoyne Sub-basin was an elevated area which served to direct sediment (between its eastern margin and the Precambrian hinterland) to the north and south, before eventual deposition in the northern Carnarvon Basin (in the Exmouth, Barrow and Dampier Sub-basins) and the Perth Basin. An exception is in the central southern Gascoyne Sub-basin where the areally restricted, lacustrine Woodleigh Formation was deposited, during the Early Jurassic. No data is available concerning the western margin of the sub-basin, adjacent to the Bernier Platform. In the deepest part of the northern Carnarvon Basin, seismic data suggest more than 5500 m of Jurassic sediments are present. Most of this sequence is fine grained and argillaceous, but there were several local areas of sandy deposition.

In the Carnarvon Basin, deposition continued from the Triassic into the Early Jurassic in the transgressive-regressive cycle which, in the Dampier Sub-basin, began in the Rhaetian and finished in the Hettangian. In parts of the Exmouth and Barrow Sub-basins, this cycle appears to have persisted until the Toarcian-Aalenian, because no break or clear lithological change can be seen in the Late Triassic to Toarcian interval (*e.g.* in Bundegi 1, Yardie East 1 and Jurabi 1).

The main Jurassic phase of sedimentation began in most areas in the early Sinemurian, when there was a transgression and a marked reduction in clastic supply. A brief phase of shallow-marine to shoreline, carbonate-dominated deposition occurred, followed by rapid deposition of the fine-grained terrigenous sediments of the lower Dingo Claystone. The transgression was followed by a regression which led to sandstone deposition, except in the central portions of some sub-basins. The regression culminated in the Callovian "Main Unconformity" (Crostella and Barter, 1980), which can be recognized over most of the North West Shelf, generally being absent only in the deepest parts of the basins. Transgression after this event led to deposition of the upper part of the Dingo Claystone. This was terminated in most areas in the Tithonian-Kimmeridgian when sands prograded into the basin, although argillaceous deposition locally halted as early as the Late Callovian (Hermite 1), or continued into the Cretaceous in the central parts of sub-basins.

The Jurassic phase of deposition finished in the latest Jurassic to earliest Cretaceous, when the Barrow Group prograded northwestwards over the Barrow Sub-basin. Elsewhere, deposition was localized or there was a brief hiatus, rather than the chronostratigraphic subdivision used by Woodside, with some additions because of the greater complexity of the Dampier Sub-basin compared to the Barrow and Exmouth Sub-basins. Some formations are time equivalent, so the dominant formation, the Dingo Claystone, is described first, then the sandy sequences from south to north.

DINGO CLAYSTONE

Definition

The Dingo Claystone (McWhae and others, 1958) has its type section in Cape Range 2 between 1130 and 4624 m. The base was not reached in this section and the top is eroded. The unit is mostly conformable on the Triassic–Lower Jurassic Mungaroo Formation, Brigadier Formation or North Rankin Formation. The Neocomian Barrow Group or (where present) the Dupuy or Angel Formations, conformably overlie the Dingo Claystone, and it thus spans nearly all the Jurassic. It also grades laterally into the Learmonth, Biggada, Dupuy, Legendre and Angel Formations. These are coarser grained siliciclastic, lateral-facies variants of the Dingo Claystone, important enough to warrant recognition as separate formations. Facies distributions are shown in Figure 80. The Dingo Claystone contains an intra-Callovian

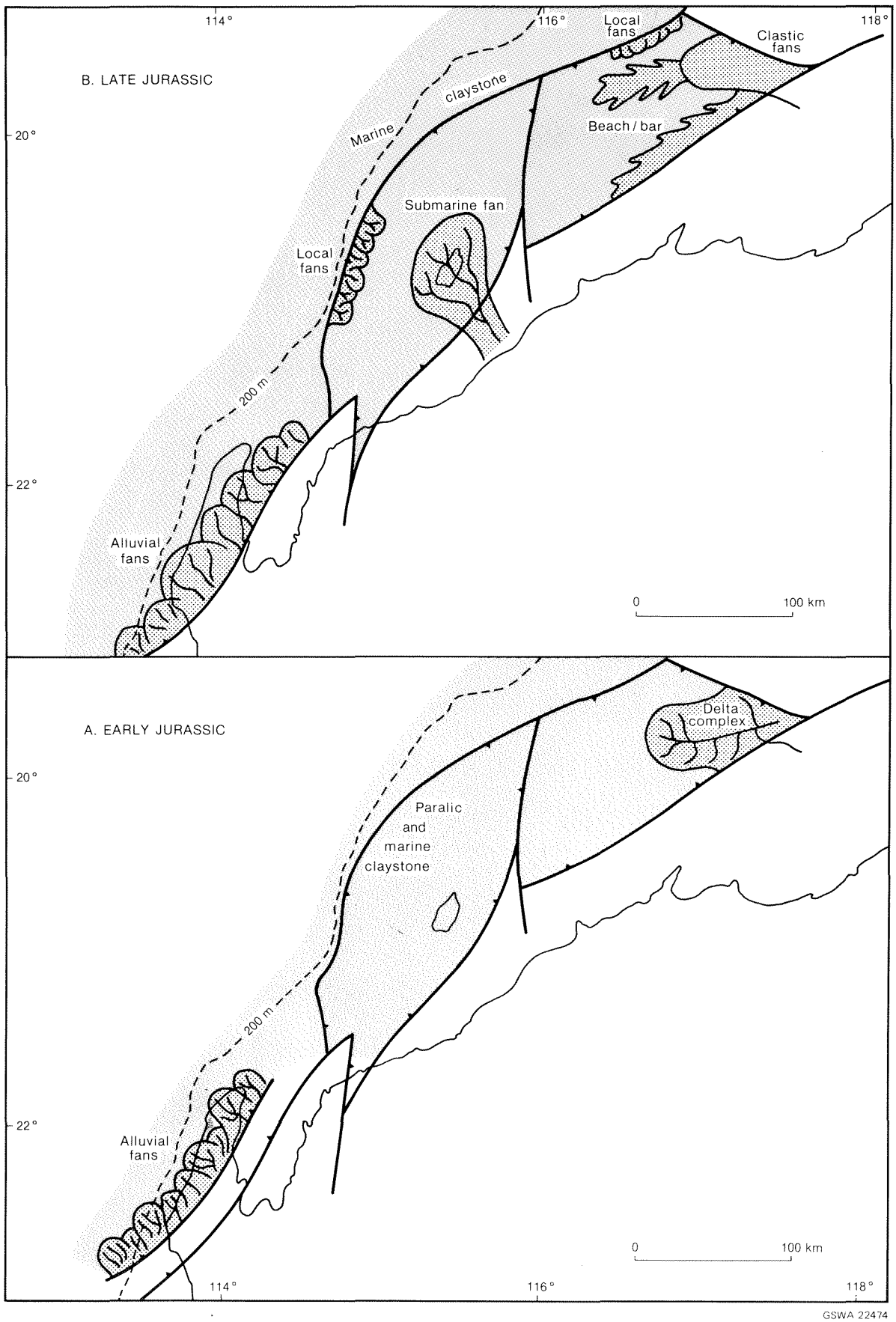

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Figure 80. **Jurassic palaeogeography. A. Early Jurassic. Areas of sandy progradation (Learmonth Formation in Exmouth Sub-basin, Legendre Formation in Dampier Sub-basin) into basinal clays (Dingo Claystone) shown by heavy stipple. Woodleigh Formation in southern Carnarvon Basin omitted. B. Middle-Late Jurassic. Sandy progradation into basinal clays by Learmonth Formation (Exmouth Sub-basin), Biggada Formation (Barrow Sub-basin) and Angel Formation (Dampier Sub-basin). Dupuy Formation is similar to Biggada Formation and is omitted.**

unconformity (the "Main Unconformity" noted by Crostella and Barter, 1980), except in the deepest parts of sub-basins, and this should lead to an expanded stratigraphy, when additional data from recent wells become publicly available.

Lithology

The descriptive term claystone is perhaps unfortunate because the lithology is generally closer to a siltstone, and the unit was originally referred to as the "Dingo Siltstone" in internal WAPET reports. Although very widespread and thick, the Dingo Claystone has a very consistent lithology, dominated by grey argillaceous siltstone. The sediments grade into claystone and locally show well-developed shaly lamination. A reduction in clay content commonly results in fine-grained sandstone as grain size increases. Pyrite (as isolated aggregates, burrow fillings, pods or stringers), mica, glauconite and carbonaceous grains are common. Scattered quartz grains are commonly present, disseminated through finer sediments.

The Dingo Claystone is usually moderately calcareous and contains calcite and dolomite nodules. These are sufficiently abundant locally to form thin limestone horizons (*e.g.* in Paterson 1, Peak 1). The lower part of the formation is the most calcareous, with relatively thick limestone or carbonate-rich intervals. These intervals were deposited in relatively shallow high-energy water, as they are commonly oolitic or rich in bioclastic fragments (Crostella and Barter, 1980). Associated fine sandstone units are cemented by carbonate.

A basal calcareous interval is present in many wells. The interval ranges from recrystallized calcarenite to dolomitic claystone to calcareous sandstone, and can be recognized by its markedly higher carbonate content in comparison to overlying and underlying units. A sand-rich interval commonly overlies the calcareous interval, and in some wells justifiably has been assigned to the Learmonth Formation (*e.g.* Bundegi 1). Intersections of the basal calcareous interval are: Bundegi 1, 2699–2820 m; Yardie East 1, 4846–4911 m (drilled depth), Hermite 1, 2140–2206 m; and Brigadier 1, 3534–3557 m.

Distribution and thickness

The Dingo Claystone is known through most of the Exmouth, Barrow and Dampier Sub-basins. The margins of these sub-basins form the limits of deposition. The sequence in North Rankin 4 suggests that it was deposited in the Victoria Syncline region but it is absent on the higher parts of the Rankin Platform, the Alpha-Hilda Arch, and the Exmouth Plateau.

The thickest section is 3494 m in Cape Range 2, the type section, but here the Tithonian uppermost part of the formation has been eroded, and the base was not penetrated. A stratigraphically complete section is in Anchor 1, where Early Jurassic sediments were reached at total depth and Dingo Claystone deposition continued into the latest Jurassic, apart from a possible Callovian disconformity. This section is only 1419 m thick because of its setting in a basin flank position. Seismic data suggest a depocentre just north of Barrow Island, where the unit is probably 5500 m or more in thickness.

Fossils and age

The dating of the Dingo Claystone is based mainly on microplankton although spores, foraminifers, ammonites (Arkrell, *in* McWhae and others, 1958), and bivalves (Cox, *in* McWhae and others, 1958) have also been used. Fossil assemblages are in places sparse and monospecific, suggesting a hostile environment.

The Dingo Claystone spans most of the Jurassic. The most commonly cited age of the basal-limestone interval is Sinemurian (although it appears to be younger in the Exmouth Sub-basin). Around the margins of the sub-basins, deposition of the sands which overlie the Dingo Claystone generally began in the Tithonian.

Environment of deposition

The lithology and fauna of the Dingo Claystone indicate that it was deposited in mostly quiet marine conditions, with only minor current influences. Major growth faults controlled deposition, and water depths were probably of the order of 200 m. The rate of deposition was rapid and probably kept pace with subsidence. The probable turbidites of the Biggada Formation, which occurs within the Dingo Claystone in the Barrow Sub-basin, indicate unstable upslope conditions and subsidence rather than very deep water.

Economic aspects

Most of the oil found in the Carnarvon Basin is of Jurassic origin (Thomas 1978; Robertson Research, 1979; Philp and others, 1980; but see also Alexander and others, 1980) making the Dingo Claystone the probable source rock for most of the important hydrocarbon discoveries.

LEARMONTH FORMATION

Definition

The Learmonth Formation (McWhae and others, 1958) is a Jurassic sand-dominated sequence along the southeastern margin of the Exmouth Sub-basin. Syndepositional movement on major faults controlled the distribution of the formation, which is an alluvial to shallow submarine-fan complex at the foot of a fault-induced mountain front. On this basis, the time-equivalent sediments in the Dampier Sub-basin which were assigned to the Learmonth Formation by Crostella and Barter (1980) must excluded from it, as they are delta-front and delta-plain deposits, not related to growth faulting. They are here named the Legendre Formation.

The type section of the Learmonth Formation is in Rough Range 1 between 1216 and 1890 m. Here, the unit is overlain, probably unconformably, by the Wogatti Sandstone and the base is faulted out by the Rough Range Fault. Further into the basin, in Sandy Point 1 and 2, the Learmonth Formation is conformable within the Dingo Claystone. In some wells, it occurs immediately above the basal limestone of the Dingo Claystone.

Lithology

The dominant lithofacies is very pale grey, generally fine-grained, micaceous sandstone with scattered medium and coarse grains throughout. The grains are usually equant although roundness is very variable. Angularity is commonly due to authigenic overgrowth, which may be inherited, but some silica and calcite cement has clearly developed after deposition. A small percentage of large, clear, mica grains is characteristic. Thin horizons showing enrichment of carbonaceous grains are locally present. Very coarse sandstone and quartzose conglomerate, with clasts up to 2 cm diameter, occur as thin interbeds. Angular claystone clasts up to 1 cm long are also present.

Siltstone with abundant conspicuous white mica and an argillaceous matrix is common, and occurs as thick, vaguely mottled, massive units. The mottling may be due to either burrowing animals or plant rootlets. Isolated, fragmented shells including belemnites and ammonites occur at a few horizons. In cores and cuttings the matrix is generally brown, but this ranges to red and purple, strongly colouring the entire rock. These bright colours are largely due to oxidation in the 20 years since most cores were cut, as in the fresh state most rocks were brownish grey, with only minor bright colouration.

Mid- to dark-grey silty claystone occurs as interbeds in the siltstone. Large plant fragments can be seen in bedding planes and there are uncommon 2 mm thick bright coal splits. Numerous coal seams are present in shaly parts of the sequence (*e.g.* Rough Range 1, 1785–1825 m).

The Learmonth Formation shows marked lateral-facies changes. Sandstone and conglomerate were deposited in the Rough Range area, while only siltstone with rare thin sandstone interbeds were deposited in Paterson 1, situated 15 km away.

Distribution and thickness

The Learmonth Formation only occurs in the Exmouth Sub-basin, flanking the Paterson and Rough Range Faults (Fig. 80A). It extends for some distance parallel to the faults, but downslope extent appears to be severely restricted.

The 674 m type section, which has a faulted base, is the thickest known section. The 312 m thick section in Sandy Point 1, between 1614 and 1926 m, is the thickest complete section, and is shown in Figure 81.

Fossils and age

Plant microfossils, microplankton, foraminifers, brachiopods, bivalves, belemnites and ammonites occur in the Learmonth Formation. Large fragmentary plant remains are abundant in some shales, and probably collected in interdistributary areas and between fans.

The Learmonth Formation is notably diachronous, as its age depends on the time of the faulting in the Exmouth Sub-basin. Sections of Learmonth Formation range in age from ?Sinemurian in Sandy Point 2, west of the Paterson Fault, to late Tithonian in Whaleback 1, east of the Paterson Fault.

Environment of deposition

The lithology, presence of both coal and marine fossils, fault-controlled distribution and relatively low down-dip continuity, in the Learmonth Formation, suggest an environment that ranges from alluvial-fan to shallow submarine-fan settings. The lateral extent parallel to faults (*e.g.* from Whaleback 1 to Rough Range 1) indicates that more than one fan is present.

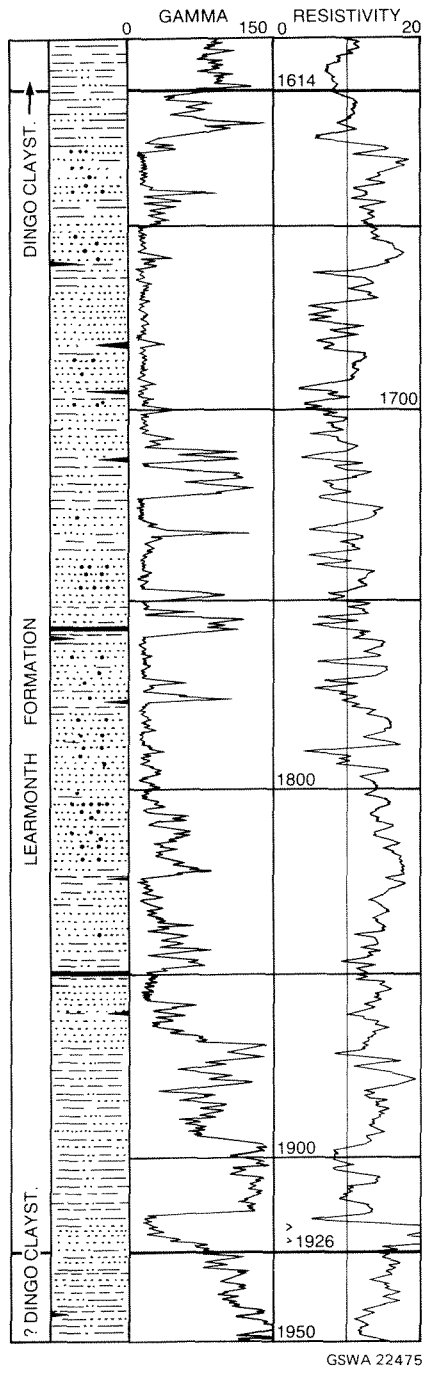

Figure 81. SP and resistivity logs, Learmonth Formation in Sandy Point 1, 1614–1926 m.

Electric logs in several wells show barrel shapes in coarse sandstone and conglomerate intervals (*e.g.* large parts of Rough Range 1 and Whaleback 1) which suggest an upper- or middle-fan position. Other wells such as Learmonth 2 show strong serration in electric logs, indicating rapid changes in the energy of the environment such as would occur in the middle to lower fan. All thick sand beds are sharp based and fine upwards, and are probably channel deposits, while thin sand beds are more variable and are probably associated with sheet flooding.

The fan complex formed west of the Paterson Fault in the Early Jurassic, and west of the Rough Range Fault in the Middle to Late Jurassic (Fig. 80).

BIGGADA FORMATION

Definition

The Biggada Formation is a sequence of Callovian sandstone within the Dingo Claystone in the Barrow Sub-basin which was previously informally referred to by WAPET as the "Biggada Beds". The type section (Fig. 82) is in Barrow Deep 1 between 3229 and 3617 m.

Lithology

The Biggada Formation consists of three sandy zones separated by fine-grained sediments typical of the Dingo Claystone. The sandstones are generally white, or brown if a clayey matrix is present. They are mostly fine to medium grained, ranging overall from very fine grained to very coarse grained, mostly moderately sorted, and subangular to subrounded. The sandstone is indurated when a clay matrix, or a silica or calcite cement is present, but is otherwise relatively unconsolidated. This is because the formation is currently within a zone of supernormal pressure where overburden pressure is supported by pore fluid, rather than grain-to-grain contact.

Distribution and thickness

The Biggada Formation is known only from the Barrow Island area, but this is probably due to the lack of deep wells elsewhere in the Barrow Sub-basin. If it is a turbidite deposit, a central basinal distribution is logical, and the Barrow Island area may be on the southeastern edge of the main deposit. The sands show a rapid lateral variation in thickness, and the 388 m thickness of the Barrow Island area may be exceeded in the basin centre.

Fossils and age

Poorly preserved palynomorphs (including microplankton) suggest a Callovian age. In areas where it is present, the "Main Unconformity" marks the end of Biggada Formation deposition.

Environment of deposition

The association with the marine Dingo Claystone and the presence of glauconite and microplankton, in fine-grained intervals, indicates

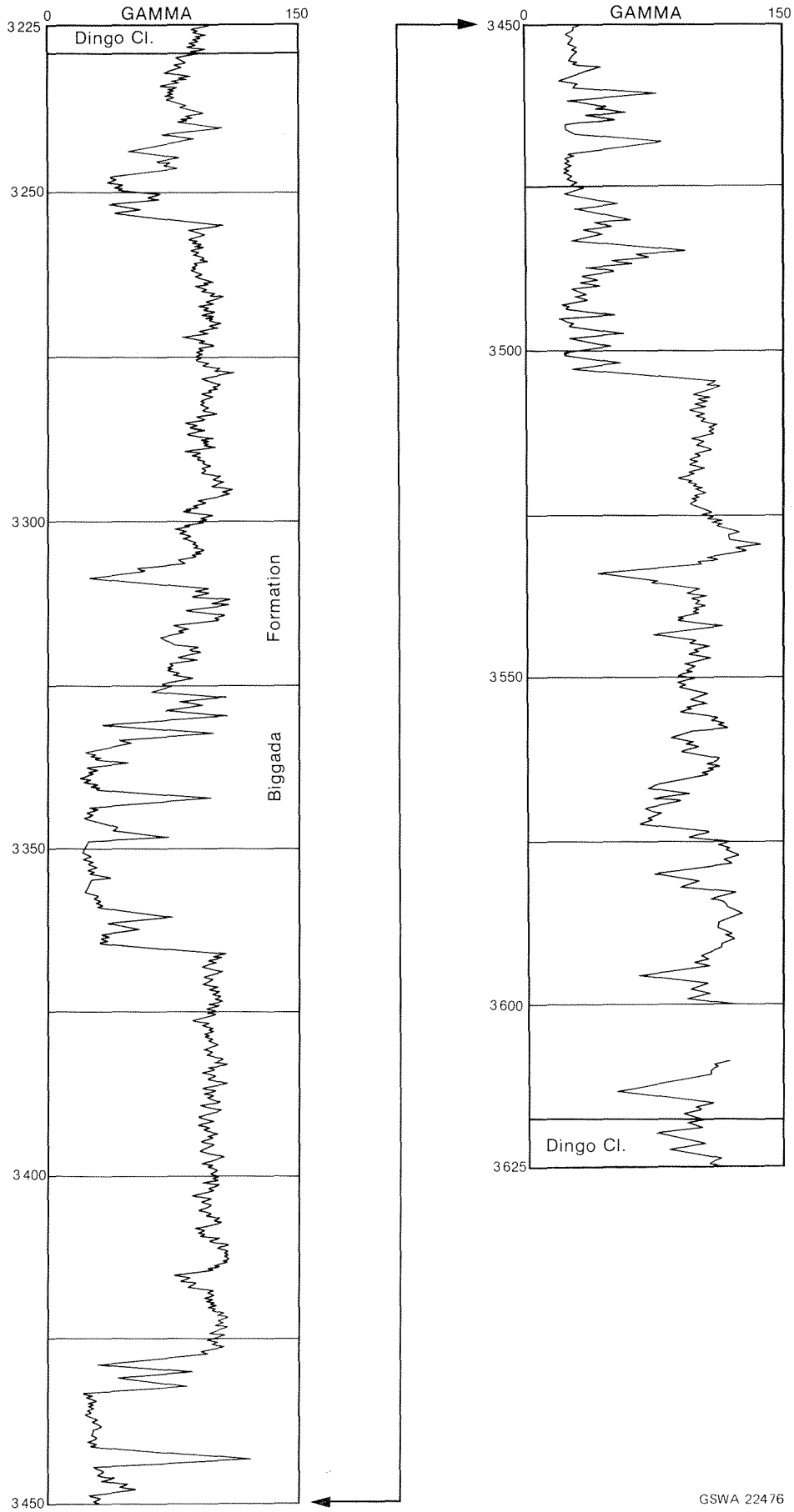

Figure 82. Gamma-ray log of Biggada Formation type section, Barrow Deep 1, 3229–3617 m.

a marine environment. The position towards the basin centre, the apparent isolation of the sand body from the basin margin, and the sharp bases and tops of sands suggest a turbidite origin. Locally, sand beds are closely stacked into compound units up to 25 m thick, some of which show mild cyclicity perhaps associated with migration or avulsion of the distributaries on the turbidite fan surface.

Economic aspects

Barrow Deep 1 found gas and gas condensate in the Biggada Formation. Electric logs indicated 247 m of gas column. Open-flow potential rates were calculated from test data to be up to 566 x 10^6 m^3/day (Crank, 1980).

DUPUY FORMATION

Definition

The Dupuy Formation ("Dupuy Member" of the Dingo Claystone of Parry, 1968; amended by Hocking, 1985) is the sequence of sandstone, siltstone and claystone which is conformable between the Dingo Claystone below and the Barrow Group above, in the Barrow Sub-basin. It is a coarser grained facies variant of the Dingo Claystone which, as well as overlying the Dingo Claystone, locally grades laterally into it. A persistent shale horizon separates the Dupuy Formation from the Barrow Group. Parry (1968) proposed a type section in Barrow 25 (Barrow BB-52J) between 2047 and 2487 m. Figure 83 shows the gamma-ray log of the Dupuy Formation in Barrow Deep 1.

Lithology

The Dupuy Formation is a repetitive sequence of interbedded sandstone and siltstone with minor claystone. The formation fines basinwards and was described by Tait (1985).

The sandstone is usually fine grained, ranging overall from very fine grained to medium grained. Some argillaceous matrix is always present, and the percentage of this determines the colour: pale grey with little matrix, darker grey to brown with abundant matrix. Grains are well rounded, and sorting varies from good to poor. Glauconite is a common accessory, with lesser white mica. Pyrite is in places abundant either as free crystals or cement. Carbonate and silica cements are both present.

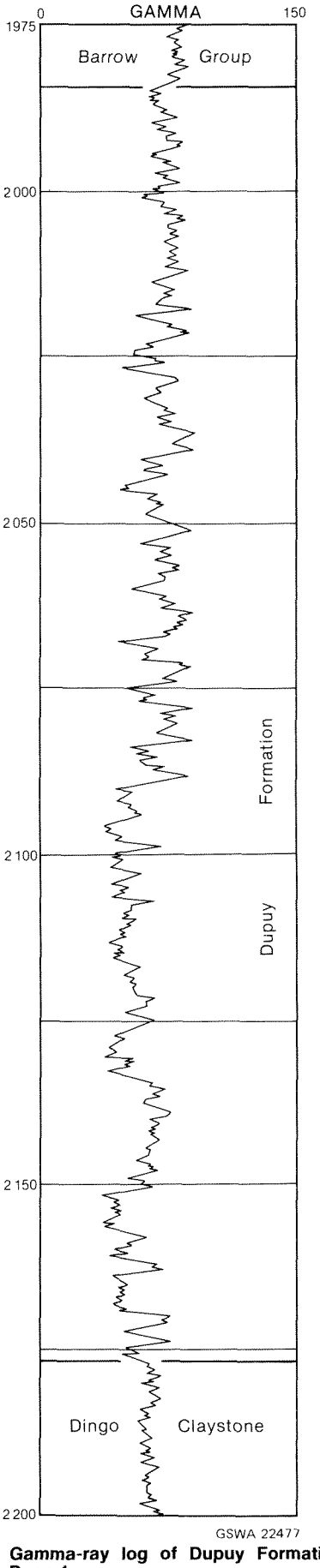

Figure 83. Gamma-ray log of Dupuy Formation, Barrow Deep 1.

The siltstone is argillaceous, micaceous and carbonaceous to (locally) lignitic. In places it grades through silty claystone to brown-grey claystone, and lenticular silty or sandy patches are present where clay is absent. Calcite and dolomite cements are characteristic. During periods of low siliciclastic supply, carbonate nodules grew in the soft sediment, and in extreme cases coalesced to form thin continuous limestone beds. These are also brown and are generally aphanitic, with rare fossil fragments.

The sandstone and siltstone form coarsening-upward cycles 15 to 30 m thick (average 18 m) which are well expressed on the gamma-ray logs for Flag 1 and Flinders Shoal 1. Thin sand horizons 1 to 2 m thick, within siltstone, have sharp bases and tops. In Pepper 1, some sand intervals are sharp based and fine upwards.

Tait (1985) recognized three sandstone facies in the Dupuy Formation: fine-grained homogeneous sandstone, bioturbated sediment, and matrix-supported intraclast conglomerate. The homogeneous sandstone occurs as sharply based layers 30 cm to 5 m thick, and grades up into bioturbated sandstone to sandy claystone. The conglomerate occurs as rare interbeds within the first two facies.

Distribution and thickness

The Dupuy Formation has been found only in the Barrow Sub-basin. It occurs in the northeastern part of the basin, being best developed along the eastern margin and extending west to Barrow Island (but not as far as Tryal Rocks 1) and south to the Pasco Islands. Time-equivalent sands in the Dampier Sub-basin are assigned to the Angel Formation because they have a different sediment source and are spatially separated. They should not be placed in the Dupuy Formation.

The thickest section is over 450 m in Flat 1. There is a similar thickness of Dupuy Formation in Flinders Shoal 1, and 350 m in the Barrow Island area. The Dupuy Formation thins both basinwards and shorewards from this axis, as shown by Tait (1985).

Fossils and age

The Dupuy Formation contains a limited microfauna and microflora, and a macrofauna of which the most useful components are ammonites. The formation is mainly Tithonian, although in Hermite 1 sandy deposition began in the latest Callovian.

Environment of deposition

The Dupuy Formation was deposited entirely in marine conditions. This is indicated by the presence of glauconite and the floral and faunal assemblage. The generally conformable relationship with the Barrow Group suggests that it was deposited as turbidite sands, on a gently sloping coalescing submarine-fan complex. Within this turbidite–submarine-fan setting, the coarsening upward cycles are probably prograding outer-fan lobes and smooth suprafan lobes on the mid fan, as shown by Mutti and Ricci Lucchi (1974, Fig. 2) and Walker (1979, Figs 13 and 14). The fining-upward cycles in Pepper 1 may be mid-fan channels, and sharply bounded sandstone beds are probably distal turbidites.

Tait (1985) described the depositional environment of the Dupuy Member in some detail, and proposed a northwest-facing palaeoslope. This implies a Pilbara Block–Hamersley Basin provenance.

Economic aspects

The first hydrocarbons to be recognized as having potential economic significance on Barrow Island were in the Dupuy Formation in Barrow 1, which was completed as a producer from this unit.

LEGENDRE FORMATION

Definition

Kaye and others (1972, Fig. 4) divided the Lower and Middle Jurassic sequence of the Dampier Sub-basin into the Enderby Formation (Lower Jurassic) and the Legendre Formation (Middle Jurassic), with the two units separated by a disconformity at the top of the Early Jurassic. No further details were given, or have since been published (except by Ludbrook, 1978, Table 1), on the stratigraphy of these two units. The disconformity was later disproved, and Crostella and Barter (1980) divided the sequence into the Dingo Claystone and the Learmonth Formation. We consider that it is unwise to extend the Learmonth Formation to the Dampier Sub-basin because of the spatial separation, and because it has a different origin to the Middle Jurassic sandy sequence of the Dampier Sub-basin. Therefore, the name Legendre Formation was resurrected by Hocking (1985), although the concept of the formation is somewhat different to that implied by Kaye and others (1972). However, the "Enderby Formation" is not used, those sediments instead being placed in the Dingo Claystone.

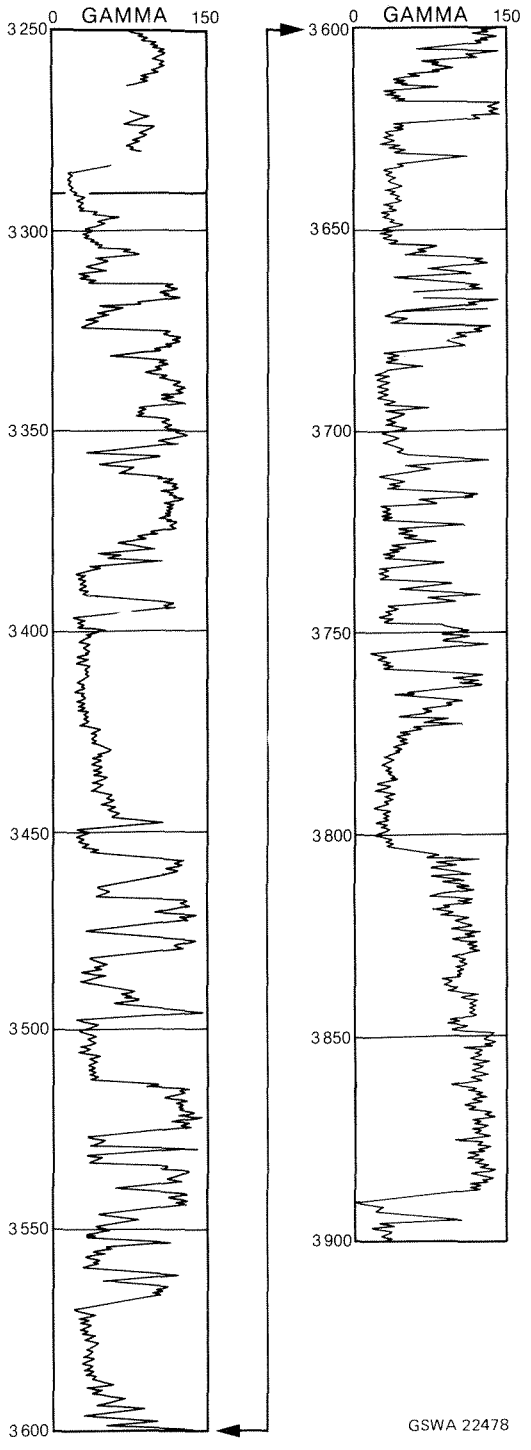

Figure 84. Gamma-ray log of Legendre Formation type section, Rosemary 1, 3284–3909 m. Base of formation not reached. Environmental interpretation: overbank clays below 3825 m, point bars at 3780 and 3600 m, distributing mouth bar at 3360 m, interdistributary bay with microdeltas from 3350 to 3305 m.

The Legendre Formation is a sandy facies variant of part of the Dingo Claystone, which was deposited in the Dampier and Beagle Sub-basins in the Early and Middle Jurassic. It conformably overlies the Dingo Claystone except on the south-eastern basin margin, where the Dingo Claystone is locally absent and the Legendre Formation unconformably overlies older rocks. The major regression and consequent "Main Unconformity" at the end of the Callovian brought deposition of the Legendre Formation to a close. The type section is in Rosemary 1 between 3284 and 3909 m, the total depth of the well (Fig. 84). Although the base of the unit was not reached, comparison with the section in Angel 1 suggests that total depth was very close to the base.

Lithology

The unifying feature of the Legendre Formation is the consistent presence of sand beds. The lithology is otherwise varied, with argillaceous rocks always present (and more abundant than sandstone in some intervals) and varying amounts of limestone. This is because deposition of the formation took place in a wide range of environments.

Sandstone intervals range from very coarse-grained (fluvial channels) to very fine-grained (deeper marine and fluvial overbank), with variable sorting and rounding. A clay matrix is common in less mature sandstone, and siliceous cement is present in all sandstone intervals (up to 25% due to burial diagenesis), with carbonate cement in more mature marine sediment. Glauconite is locally present. Sandstone in the Bathonian part of the formation is highly radioactive.

Sandstone commonly grades into siltstone, which is usually argillaceous and micaceous. Claystone is also abundant. The siltstone is commonly carbonaceous, reflecting high terrestrial input of debris. Carbonaceous material occurs both disseminated and concentrated (into thin splits); coal beds about 1 m thick are indicated by electric logs. Glauconite is present in some clearly marine sediments.

Limestone is dominant only in Hampton 1, where it occurs throughout the sequence as beds ranging from less than 1 m to more than 10 m thick. They vary from pale to dark grey-brown, from mudstone to packstone in texture, and in places contain an abundant fauna of bryozoans and gastropods.

Distribution and thickness

The Legendre Formation occurs in the eastern Dampier Sub-basin. It is present as far into the basin as Hampton 1 and Rosemary 1 to the west and Lambert 1 and the Angel Field to the

northwest, but does not extend to Enderby 1 or the North Rankin Field. The De Grey Nose may mark the northern limits of the Legendre Formation.

Hampton 1 intersected some 800 m of Legendre Formation, while the formation is probably 650 to 700 m thick in the Rosemary 1 area. The thickest development of the Legendre Formation is probably in the Legendre 2 area, where it is more than 1300 m thick.

Fossils and age

Microplankton, spores, pollen and (in limestone horizons) macrofossils have been identified from the Legendre Formation. The unit is late Early Jurassic and Middle Jurassic in age. The oldest Legendre Formation is Pleinsbachian, in Angel 2. Although a demonstrable time break is not present throughout all the Dampier Sub-basin, the marine transgression at the end of the Callovian marks the end of Legendre Formation deposition.

Environment of deposition

Sediments within the Legendre Formation were deposited in a wide range of environments, ranging from fluvial areas high on the delta plain to marine shelf. Deposition was controlled by a major river system located in the northeastern corner of the Dampier Sub-basin. The drainage system may have been influenced by the De Grey Nose, with the river mouth located just to the south. In the Early Jurassic, the basin was probably shallow and deltaic sands prograded westwards rapidly. The approach of the delta is clearly seen in Angel 2 at about 3650 m, where a number of coarsening-upwards sand cycles represent the progradation of distributary mouth-bar sediments into the basin. After 300 m of intermittent sand deposition, the delta displaced all marine influence and sandy fluvial deposition became firmly established. Delta-top sediments reached Rosemary 1, and associated marine sandstone from the fringes of the delta reached Hampton 1, Lambert 1, and the Angel Field area. Tectonism accelerated in the Middle Jurassic and the basin deepened. As a consequence the delta became wave dominated and the area over which fluvial deposition took place decreased, with a corresponding increase in marine coastal deposits. A marine transgression at the end of the Callovian, following the "Main Unconformity", terminated Legendre Formation deposition.

Typical fluvial sediments are well developed in the type section in Rosemary 1. Here, the gamma-ray log clearly shows sand packages with abrupt bases and fining-upward tops typical of point-bar deposits. Overbank deposits (including coal) occur between point bars and vary from thick claystone packages to packages of thin sand, which may be crevasse splays or the point bars of shallow tributaries to the main river (Fig. 84).

The return to basinal deposition is also well shown in Rosemary 1. In the upper 100 m the sands oscillate between point-bar and distributary mouth-bar deposits before basinal shales return again (Fig. 84).

Marine coastal deposits are present in Hampton 1, where beds of sandstone with commonly associated limestone occur within a dominantly siltstone and shale sequence. Sediments brought to the basin edge by fluvial processes were resorted by wave or tidal energy, and the clays winnowed and transported basinwards. Limestone accumulated as shoals derived from debris of organisms. In the Legendre area, a thick sand sequence is probably also a marine-reworked deposit. Large parts of the section are almost wholly sandstone and appear to be shelf to shoreface deposits, of wave-sorted sediment.

ANGEL FORMATION

Definition

Kaye and others (1972) placed the fine-grained Jurassic sediments above the Callovian "Main Unconformity" in the Dampier Sub-basin in the "Dampier Formation", and the sandy sequence from the northwest Dampier Sub-basin in the "Dupuy Sand Member". However, the name "Dampier Formation" is preoccupied by the Dampier Limestone, a Pleistocene unit from the Shark Bay area defined by Logan, Read and Davies (1970). Also, work since 1972 suggests that the Upper Jurassic silty shales in the Dampier Sub-basin can be assigned to the Dingo Claystone, and that the Dupuy Formation, as amended, should be restricted to the Barrow Sub-basin. Therefore, the Angel Formation was proposed by Hocking (1985) for the sandy sequence which was deposited in the Dampier Sub-basin, after the Middle Jurassic transgression (Fig. 80B), and which Kaye and others (1972) equated with the "Dupuy Sand Member". The type section is in Angel 1 between 2655 and 3167 m (Fig. 85). It conformably overlies the Dingo Claystone and may be conformably or unconformably overlain by Cretaceous claystone.

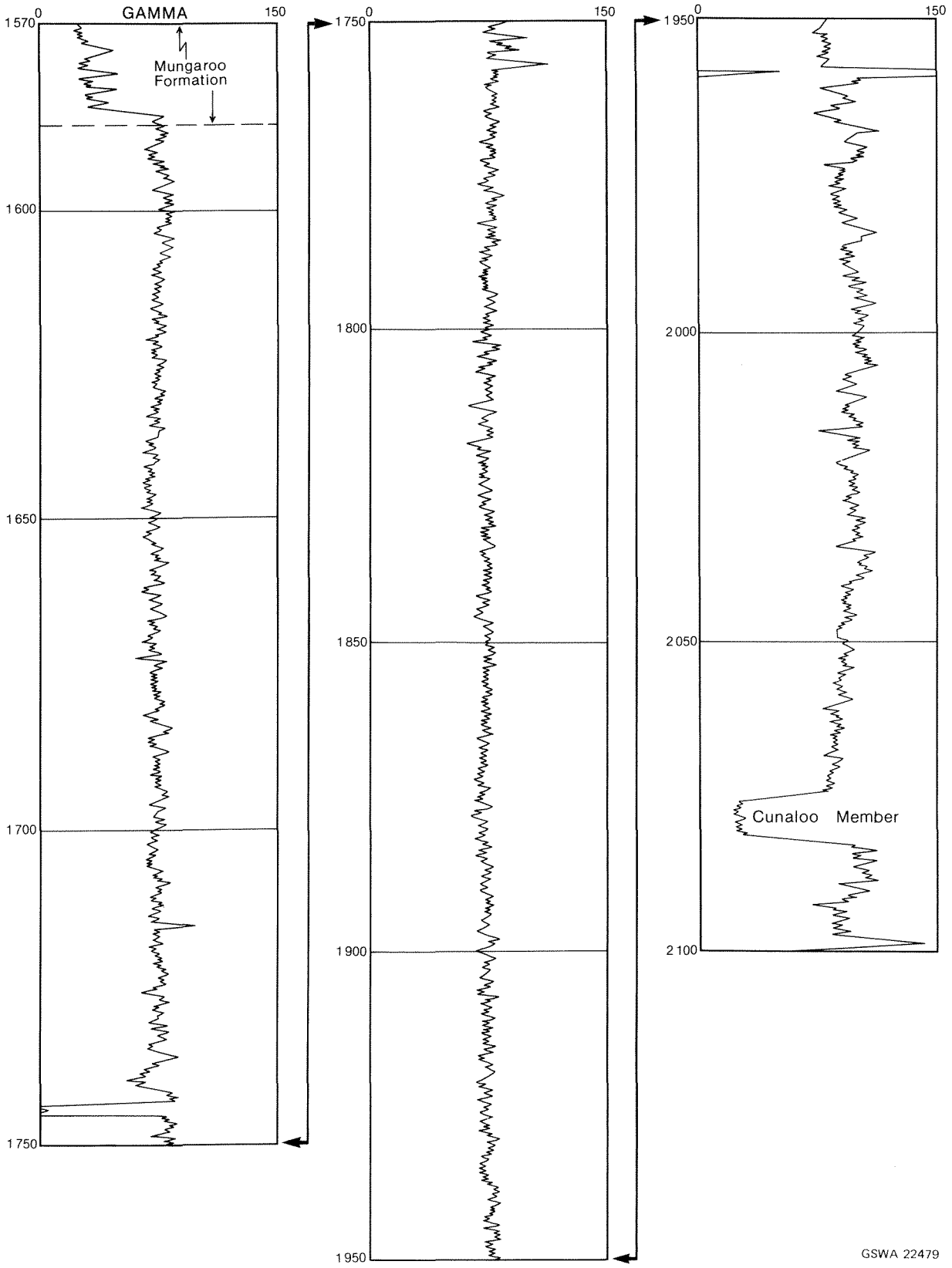

Figure 85. Gamma-ray log of Angel Formation type section, Angel 1.

Lithology

The Angel Formation consists mostly of pale-grey sandstone, generally medium to fine grained but ranging from granule to silt size, with generally less than 5% argillaceous matrix. Grains are usually subrounded and moderately to well sorted. Glauconite and pyrite are minor accessories. Siderite is a common cement (up to 15% by volume), and silica cement is present in some intervals.

Siltstone ranges from a well-winnowed finer variant of the sandstone, to highly argillaceous. The colour ranges from pale grey to a darker grey where clay matrix is present. Trace glauconite and pyrite are again commonly present. Claystone, when present, is usually silty, contains glauconite and pyrite, and is mid to dark grey.

Distribution and thickness

The formation is confined to the northeastern corner of the Dampier Sub-basin, presumably adjacent to the point of sediment supply. It extends along the southeastern margin at least as far south as Rosemary 1, but probably was confined entirely to the Dampier Sub-basin and never reached the Barrow Sub-basin. The Lewis Trough was a barrier to the westward migration of the sand, and only thin sands occur in Dampier 1 and Madeleine 1. In the northern part of the basin the trough was shallower and sand reached as far west as Lambert 1 and possibly to Egret 1. The section in Egret 1 is condensed, and it is not clear whether the sediments there had an easterly source or were derived from the Rankin Platform on the western margin of the sub-basin.

The thickest section penetrated is nearly 750 m in Angel 3, and from here the formation thins in all directions. It is only 180 m thick in Egret 1, and, along the southeastern margin of the basin, approximately 450 m thick in Legendre 1 and 300 m thick in Rosemary 1.

Fossils and age

Sandstone intervals of the Angel Formation are generally barren, but the intercalated shales are in places rich in microfossils. Microplankton are abundant, indicating marine conditions, and there is a strong terrestrial contribution of spores, pollen and other plant material.

The unit is Tithonian to earliest Neocomian in age, although in the Legendre area it may extend down into the Callovian.

Environment of deposition

The tectonic events at the end of the Middle Jurassic changed the configuration of the Dampier Sub-basin so that the northeast corner became a marine area rather than a fluvial dominated area. Sediments brought in by the major rivers were distributed by marine processes across and around the basin margin, forming strandline, shallow-water and deeper marine deposits.

The Angel Field area is relatively close to the sediment source, as the sorting of the sands is only moderate, a kaolin matrix is present, and some sands contain subangular as well as subrounded grains. In the Legendre area the grains are better sorted, moderately rounded, and the clay matrix is largely absent. Beach/bar deposits and perhaps even subaerial dune deposits may be present. Further north in Lambert 1 the sandstone is still relatively coarse grained, indicating moderate energy levels, but sandstone and shale commonly alternate, suggesting either a water depth near wave base or deeper turbidite deposition. Large-scale fining-upward cycles and a 50 m siltstone interval suggest that the rate of subsidence of the basin was not in balance with the sediment supply.

Although the main clastic supply appears to have been the De Grey Nose, as in the Lower Jurassic, other sources may have existed. The southwards movement of sediment extended as far south as the Legendre 1 area, with sand less abundant and more restricted stratigraphically further south in Lewis 1. However, further south in Rosemary 1, sands are again common in the Tithonian sequence, which together with the apparent bypass of the Lewis 1 area suggest a second source close to Rosemary 1. In addition to these two sources, there may have been a westerly source, from the Rankin Platform in the Egret 1 area.

WOODLEIGH FORMATION

Definition

The Woodleigh Formation ("Woodleigh Beds" of McWhae and others, 1958; amended by Denman and others, 1985) is only known from water bores in the Woodleigh Station area. The type section is in Woodleigh 7 water bore between 210 m and 235 m (total depth). It is a fine-grained clayey sequence which is unconformable beween the Birdrong Sandstone and older rocks.

Lithology

Lithological data on the Woodleigh Formation are sparse, since it is known only from some water bores on Woodleigh Station. The drillers' logs for these bores are not detailed, and cuttings are no longer available. The formation appears to be a uniform sequence of soft, grey, slightly pyritic claystone to shale.

Distribution and thickness

The Woodleigh Formation is restricted to the Woodleigh Station area. Even here, it is only present in some bores: in other bores the Birdrong Sandstone rests directly on Silurian sediments. In Woodleigh 1981/2, a unit resembling the Woodleigh Formation was intersected between 121 and 171 m. The unit underlies the Birdrong Sandstone and rests unconformably on granitic basement (Richardson, 1981). However, the unit lacked the fossil assemblage characteristic of the Woodleigh Formation, and instead it may be a localized Lower Cretaceous deposit. Other than this possible intersection, the base of the Woodleigh Formation has not been encountered. The maximum recorded thickness is 91 m, in Woodleigh 2 water bore.

Fossils and age

The Woodleigh Formation contains abundant spores and pollen which date the formation as Early Jurassic (Balme, *in* McWhae and others, 1958). No marine organisms have been found.

Environment of deposition

The lack of marine organisms, the fine-grained lithology, and the restricted distribution suggest that the Woodleigh Formation formed in a restricted, possibly fault-bounded lake.

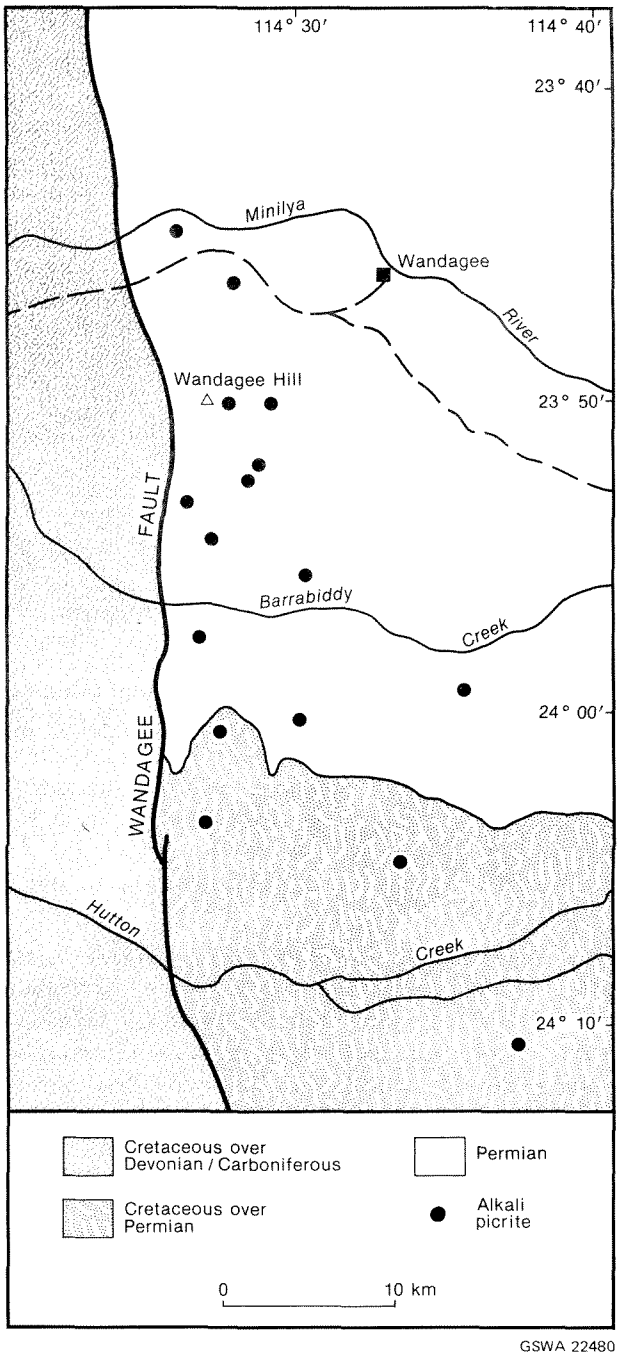

Figure 86. Location of known "kimberlitic" intrusive rocks in the Wandagee area. Data from Atkinson and others (1983).

ALKALI-PICRITE INTRUSIVES

Reconnaissance exploration for kimberlites by CRA Exploration Pty Ltd in 1978–79, using stream sampling and airborne magnetic surveys, revealed the presence of 16 pipes and dykes with kimberlitic affinities in the Wandagee area. These have been described in some detail by Atkinson and others (1983, 1984), and by Jaques and others (1986); from these descriptions the following details are taken.

The pipes and dykes occur in an elongate north-trending zone some 50 km in length, termed the Wandagee Province, located immediately east of the Wandagee Fault and Ridge, and centred on Wandagee Hill (Fig. 86). The pipes intrude Permian sediments, and have virtually no ground expression. In the south of the province, some pipes are covered by up to 158 m of Cretaceous Winning Group.

Both magmatic rocks and tuffs are present in the cluster of occurrences. Magmatic rocks are found as dykes and sills, and were described as alkali picrites by Jaques and others (1986), having much in common with kimberlites. They contain 45% olivine, 45% clinopyroxene and minor matrix

material, including analcime. In unweathered rock the porphyritic olivine occurs as large subhedral to euhedral phenocrysts from 0.4 to 2.0 mm. Large rounded xenocrysts of granular olivine up to 10 mm across are rare. The groundmass consists of a plexus of stubby prisms of greenish to faint purplish brown clinopyroxenes together with minor brown mica and devitrified glass.

The tuffs are extensively weathered in trench exposures and show considerable alteration in drill core. They are clast supported with well-rounded phenocrysts of olivine, now pseudomorphed by talc, carbonate and chlorite, forming 15–25%. The remainder of the clasts are predominantly subrounded porphyritic igneous types. Minor clasts of pyritic shale and micaceous siltstone are also present.

While the magmatic rocks have major-element geochemistry resembling "classic" kimberlite, they are abnormally soda rich. They are relatively poor in potash and "incompatible elements," and therefore constitute a separate Western Australian type. Heavy-mineral concentrates from the Wandagee alkali picrites contain coarse pyrope, chrome diopside, magnesian chromite, magnetite, picroilmenite, zircon, and rare diamonds.

Ten diatremes, ranging up to a maximum of 14 hectares in area, occur in the cluster. These are thought to be within the pipe zone of the volcano because of the absence of bedding and steep contacts with country rock. The material within these pipes consists mainly of alkali-picrite tuff with abundant spherical, nucleated alkali-picrite autoliths indicative of gaseous emplacement. The remainder of the Wandagee alkali-picrite bodies are thin (up to 3 m) westerly dipping sills intruding Permian siltstones of the Byro Group. The sills consist of magmatic alkali picrite. This is dense dark grey and fresh, in contrast to the heavily weathered and altered tuffs.

One of the diatremes has been dated using U-Pb methods on xenocrystal zircon at 160 ± 10 Ma (Atkinson and others, 1984), which confirms the Jurassic age suggested by the relationship of the alkali picrites to the established Permian and Cretaceous sequences.

CHAPTER 9

Cretaceous

Major changes in the style and extent of deposition occurred during the Cretaceous in the Carnarvon Basin. After the strong tectonic activity of the Jurassic, a period of relative quiescence ensued. The main depocentres, as in the Triassic and Jurassic, were in the Barrow and Dampier Sub-basins. After the late Neocomian, deposition also extended over all but the easternmost Carnarvon Basin as a result of a major rise in sea level. Prior to this, erosion of the area south of the Exmouth and Barrow Sub-basins provided source material for the Barrow Group, a sandy deltaic complex up to 1200 m thick. In the Dampier Sub-basin, sand deposition continued for a short time into the Cretaceous, but argillaceous sedimentation was dominant. In the Exmouth Sub-basin, the Wogatti Sandstone, a fluvial to alluvial-fan sequence, fringed the Rough Range Fault. On the Peedamullah Shelf, the Nanutarra Formation and Yarraloola Conglomerate formed in mixed fluvial to shallow-marine environments.

Towards the end of the Neocomian, a number of factors combined to bring open-marine conditions to all but the easternmost Carnarvon Basin. Firstly, Australia separated from greater India, resulting in an extensive marine incursion along the west coast. Secondly, the relief in the onshore basin caused by the Jurassic tectonism had been almost entirely eroded away, resulting in a near-peneplained surface. Combined with eustatic sea-level rise and sinking of the continental margin, this produced open-marine conditions with substantially lessened terrigenous input, and the Winning Group, a fine-grained, dominantly siliciclastic, sequence was deposited. The continental margin continued to sink throughout the Cretaceous and, in the early Senonian, sedimentation changed to calcareous pelagic deposition. This resulted from changed oceanic-circulation patterns following continental breakup and led to the deposition of the Toolonga Calcilutite, in quiet, open-marine conditions, and the Korojon Calcarenite in slightly more energetic, shallower areas. The Miria Formation, which in onshore areas is a thin, condensed sequence, was deposited in the latest Cretaceous.

BARROW GROUP

(A. M. Tait and D. N. Smith)

Stratigraphy

The Barrow Group is a deltaic complex which prograded from the southern end of the Barrow Sub-basin towards the north. It consists of the Malouet and Flacourt Formations, which represent different major facies within the delta and are thus diachronous. Because of this, the Barrow Group is primarily discussed as a whole rather than as two formations.

The term Barrow Group was first introduced in a WAPET report by Parry (1968), for the sandy deltaic sequence of Neocomian age between the Upper Jurassic Dingo Claystone and the Muderong Shale in the Barrow Sub-basin. Parry defined the top of the group at 914 m in Barrow 1 (L–54J) and the base at 2047 m in Barrow 25 (BB–52J). Barrow 25 was used to define the base, rather than Barrow 1, because there is a wireline log-run change and a scale change near the critical depth in Barrow 1. Thomas (1974) later described the Barrow Group as being in Barrow 1 from 908 m to 1985 m, the latter being the correlative of 2047 m in Barrow 25. However, we consider the upper boundary to be 914 m. Because Barrow Island was high during deposition of the Barrow Group, a stratigraphically complete section is absent. The section in Pepper 1 is more complete (Fig. 87). The group conformably overlies the marine Dupuy Formation, or Dingo Claystone, and is overlain by the Muderong Shale. The upper contact varies from conformable to unconformable (Wiseman, 1979, Fig. 2).

The name was first published by Mollan and others (1969, Figs 7 and 8) who, along with other workers (Crank, 1973; Thomas and Smith, 1974, 1976, etc.), recognized a number of sub-units within the sequence and obviously believed that these would eventually be erected as formations. However, Playford and others (1975) reduced the unit to formation status, because it had not by then been formally subdivided. They proposed a

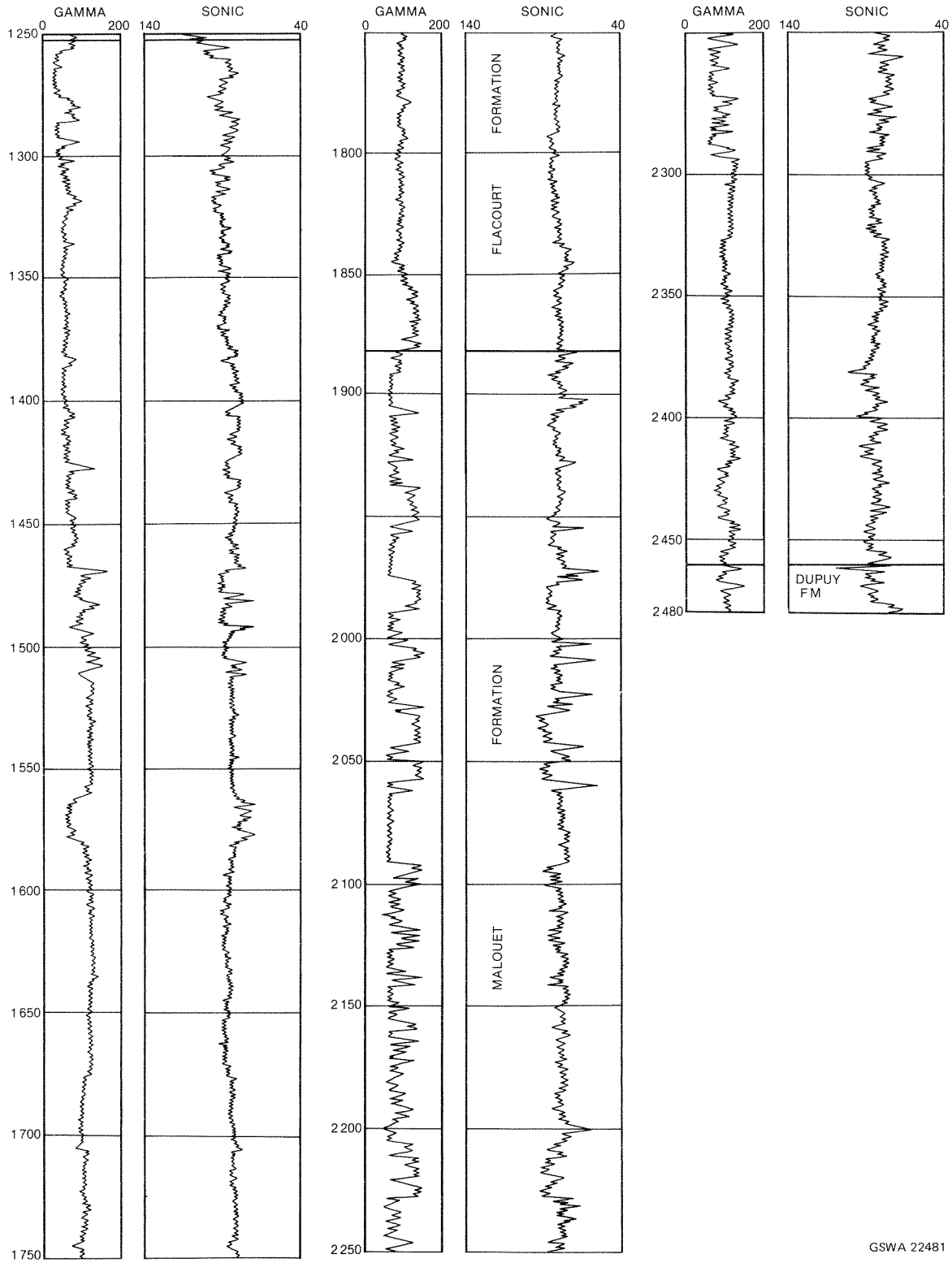

Figure 87. Gamma-ray and sonic logs of Barrow Group in Pepper 1. This section is more complete than the section in Barrow 1.

type section in Barrow 1 between 909 m and 2181 m, thereby including beds that Parry (1968) assigned to the "Dupuy Sand Member" (*i.e.* Dupuy Formation).

In later WAPET reports, Lowry (1977) suggested that the Barrow Group should be split into two units: an upper "Flacourt Formation", characterized by inclined bedding, dipping to the north; and a lower "Malouet Formation", consisting of relatively flat-lying sediments. As such, both the Malouet and the Flacourt Formations were seismic stratigraphic units. These have subsequently been widely recognized on seismic sections in the offshore Carnarvon Basin. Further work allowed Lowry (1978) to informally define the units as formations on a lithological basis and to name type sections. Lowry also included the "Dupuy Sand Member" in the Barrow Group, but it is here excluded, in accordance with the original usage of Parry (1968) and as suggested by Powell and others (1978). This is because the Flacourt and Malouet Formations together form a distinct unit, both seismically and lithologically, to which the Dupuy Formation is not related (Tait, 1985). Hocking (1985) formally reinstated the Barrow Group.

Delta-plain, delta-front, prodelta and basinal deposits can be recognized in the Barrow Group. Deposition on the delta plain and delta front was sand dominated. Silt and clay were deposited on the lower prodelta, with sand and clay in basinal areas. This resulted in gross sedimentary layers which, where there was continuous deposition during delta progradation (*e.g.* in the area from Rosily 1 to Spar 1), form an upper and a lower sandstone unit separated by a claystone unit.

The lower sandstone unit (the basinal facies, or bottomsets) is the Malouet Formation. The middle claystone unit (prodelta, or lower foresets) and the upper sandstone unit (delta front and delta plain, or upper foresets and topsets) together form the Flacourt Formation (Fig. 88). Because of the nature of this definition, the boundary between the two formations is markedly diachronous on a regional scale. Any sand horizon at the top of the Malouet Formation will, when traced south, gradually become siltier and pass up into the Flacourt Formation, but when traced north, will "dive" under other sands into the Malouet Formation. Thus, the top of the Malouet Formation is not a continuous surface of lithological contrast (*i.e.* there is no single, regionally continuous "top Malouet Sand") but is instead a diachronous surface, linking the shoreward limits of all the individual Malouet Formation bottomset sand boundaries.

Tait (1985) described the lithology, geometry and depositional environment of the Barrow Group in detail.

Distribution and thickness

The Barrow Group occurs from the Barrow Sub-basin to the Exmouth Plateau. In the Dampier Sub-basin, sediments of the same age appear to have a different provenance, and are considered to be a different unit. On the Exmouth Plateau, sediments are present which are seismically very similar to the Barrow Group in the Barrow Sub-basin, and drilling has confirmed a similar age and lithology.

The final foreset of the Barrow Group runs in an arc from approximately Investigator 1 on the Exmouth Plateau, past Gorgon 1 on the southern end of the Rankin Platform, across the northern part of Barrow Island, and meets the Flinders Fault zone south of Hermite 1. The group thins northwards from the final foreset, as only the Malouet Formation is present. Malouet Formation has been recognized as far north as Campbell 1 and West Tryal Rocks 3, and it may extend further.

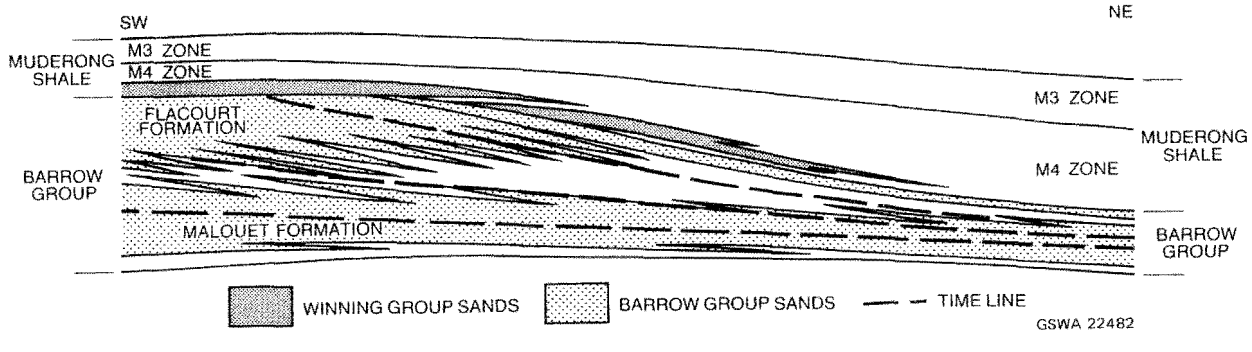

Figure 88. Seismic appearance of segment of Barrow Group delta model, after Campbell and others (1984).

Within the area bounded by Spar 1, Barrow Island, Pepper 1, Rosily 1 and West Barrow 1A, the Barrow Group is over 1000 m thick. The maximum drilled thickness is 1237 m in Pasco 2, and it may well be thicker in the undrilled area between West Barrow 1A and Barrow Island.

The Barrow Group thins towards the eastern and southern margins of the Barrow Sub-basin. Along the southern part of of the Rankin Platform and the Hilda-Alpha Arch, the Barrow Group is generally thinner than in the Barrow Sub-basin, both because of less subsidence and because of pre-existing topographic highs which were covered only by the upper parts of the Barrow Group.

Fossils and age

Though macrofossils occur within the Barrow Group, plant material is dominant because of the deltaic environment and it is the main basis of dating. Spores and pollen are abundant together with microplankton (Wiseman, 1979).

From palynological studies on Barrow Group wells, deposition of the Barrow Group began in the latest Jurassic. The delta advanced from the southern end of the Barrow Sub-basin, and in more distal areas in the north, such as Tryal Rocks 1, some 300 m of shale were deposited in the Cretaceous prior to the first sands. This indicates that sand deposition did not reach these parts till later in the Neocomian as the delta advanced. Wiseman (1979) showed that sand deposition ended in the Valanginian, north of Barrow Island, when the delta ceased to advance. Progradation of the delta stopped because of the cut-off from its feeder rivers by Early Cretaceous tectonism, associated with continental breakup (Larson, 1977), rather than because of a sea-level fall as suggested by Wiseman (1979). The delta was then gradually drowned.

Economic aspects

The first discovery of oil on Barrow Island was in sands of the Barrow Group. Unfortunately, the unit is very sandy and there is a prevalence of faults so that most structures have apparently leaked and are now dry. Any oil and gas accumulations appear to be in isolated channel sands. Nevertheless, with its excellent reservoir parameters the unit has been, and will continue to be, a prime exploration target. This is borne out by the oil occurrences in, for example, South Pepper 1. Wells on Barrow Island are still producing from Barrow Group sands.

MALOUET FORMATION

Definition

The name "Malouet Formation" was introduced by Lowry (1977), and first used, but not defined, by Campbell and Smith (1982). Hocking (1985) formalized the unit. The type section (Fig. 89) is the 616 m thick interval between 1370 m and 1985 m in Barrow 1. Through most of the Barrow Sub-basin, the Malouet Formation conformably overlies the Upper Jurassic Dupuy Formation and Dingo Claystone. As discussed above, the boundary between the Malouet and Flacourt Formations is based on gross bedform geometry and lateral facies changes, which are recognizable on seismic sections. The Malouet Formation is thus conformably overlain by and gradational into the Flacourt Formation. North of the last foreset of the Barrow Group delta (*i.e.* beyond the edge of the Flacourt Formation), the Malouet Formation is conformably overlain by Muderong Shale.

Lithology

The Malouet Formation generally consists of an upper sandstone-dominated unit and a lower siltstone-dominated unit. Between 1929 and 1986 m (upper part of Unit D of McTavish, 1965), medium to dark grey-brown micaceous siltstone is dominant, with minor brown, finely crystalline limestone and greyish, fine- to very fine-grained sandstone. All three rock types are variably pyritic and glauconitic, with pyrite nodules in the limestone. Both the siltstone and limestone are commonly sandy.

The overlying interval, from 1699 to 1929 m (Unit C of McTavish, 1965), consists of interbedded siltstone and sandstone in approximately equal amounts. The sandstone is predominantly poorly sorted and fine to very coarse grained, and contains common thin beds (<1.5 m) of calcareous sandstone. The siltstone is brownish-grey (darker with increasing depth), micaceous, pyritic, in part sandy, and slightly chloritic or glauconitic. Calcareous nodules up to 8 cm in diameter break up the otherwise massive bedding, and contain pyrite clots up to 3 mm in size.

In the type section, the interval between 1370 and 1699m (lower part of Unit B of McTavish, 1965), consists of friable, massive, moderately to poorly sorted, fine- to very coarse-grained, light-grey sandstone, with minor interbedded brownish

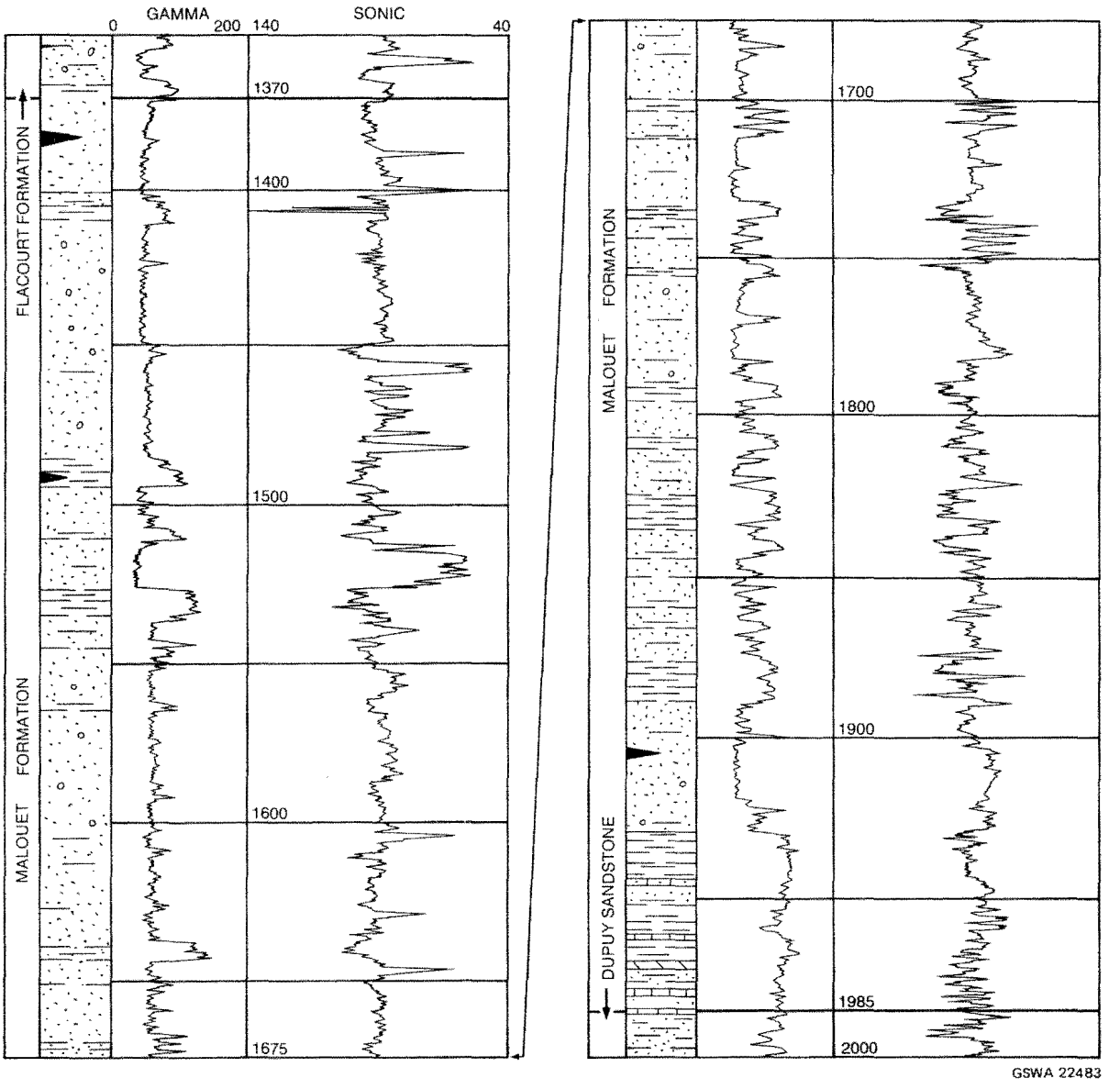

Figure 89. Gamma-ray and sonic logs of Malouet Formation type section, Barrow 1, 1370–1985 m.

lignitic siltstone and light coloured, moderately sorted, fine-grained calcareous sandstone, and rare thin beds of mottled tan and white, finely crystalline limestone.

The siltstone grades into buff to brownish-grey, slightly calcareous mudstone. The siliciclastic sediments are all micaceous, lignitic and pyritic, with pyrite nodules up to 15 mm in diameter occurring in the sandstone. The siltstone and mudstone are commonly sandy and contain variable amounts of wood fragments.

Distribution

The Malouet Formation occurs in the Barrow Sub-basin and on the Exmouth Plateau as the basinal, bottomset part of the Barrow Group delta, and has a greater extent than the overlying Flacourt Formation. It extends as far north as Campbell 1 and West Tryal Rocks 3. In the southern and eastern Barrow Sub-basin it thins and becomes silty towards the basin margin.

Environment of deposition

The Malouet Formation is the distal prodelta and basinal part, or bottomsets, of the Barrow Group delta. The sands, and some of the stiltstones and claystones, are mass-flow deposits forming fans and channel fills. Individual mass flows are generally up to a few metres thick but in places they stack to form thicker sand bodies. These mass-flow sediments were derived from the delta-top/shallow-marine part of the Barrow Group delta and transported by gravity flows down the delta foresets to accumulate in the bottomset area. The sedimentary structures in various Malouet Formation cores are diagnostic of mass-flow processes.

Definition

The name "Flacourt Formation" was introduced by Lowry (1977) and used, but not defined, by Campbell and Smith (1982) and Tait (1985). Hocking (1985) formalized the unit. The type section (Fig. 90) is in Barrow 1 between 914 and 1370 m. The Flacourt Formation conformably overlies and grades laterally into the Malouet Formation, and is overlain by the Muderong Shale. In places (*e.g.* along the slope of the last foreset) the boundary is probably conformable, with a condensed sequence on top of the Flacourt Formation due to the slow sedimentation rate at the Muderong Shale transgression. Elsewhere, including Barrow Island, erosion of the uppermost Flacourt Formation has occurred with incorporation of reworked Flacourt sand into the base of the Muderong Shale.

Lithology

McTavish (1965) recognized two units within the type section. Below 1071 m, the sequence has only rare siltstone, and consists of quartz sandstone, slightly feldspathic, similar to that in the interval above but very coarse grained with pebbly beds, containing pebbles commonly greater than 5 mm diameter and ranging up to 10 mm diameter. These are very common in the lower part of the sequence. Pyritic beds are present, mostly above 1220 m.

Above 1071 m, the sequence consists of light-brown and grey, mostly fine-grained, sandstone and sandy, locally calcareous siltstone, with traces of coal below 1055 m. The sandstone is pyritic between 1006 and 1038 m and contains carbonized plant fragments throughout. The sequence coarsens upwards.

Distribution

The Flacourt Formation extends through the southern part of the Barrow Sub-basin and on to the Exmouth Plateau as the upper part of the Barrow Group delta.

Environment of deposition

The Flacourt Formation formed the delta plain (topsets) and the delta front and upper prodelta (foresets) of the Barrow Group delta. Environments of deposition range from delta-plain

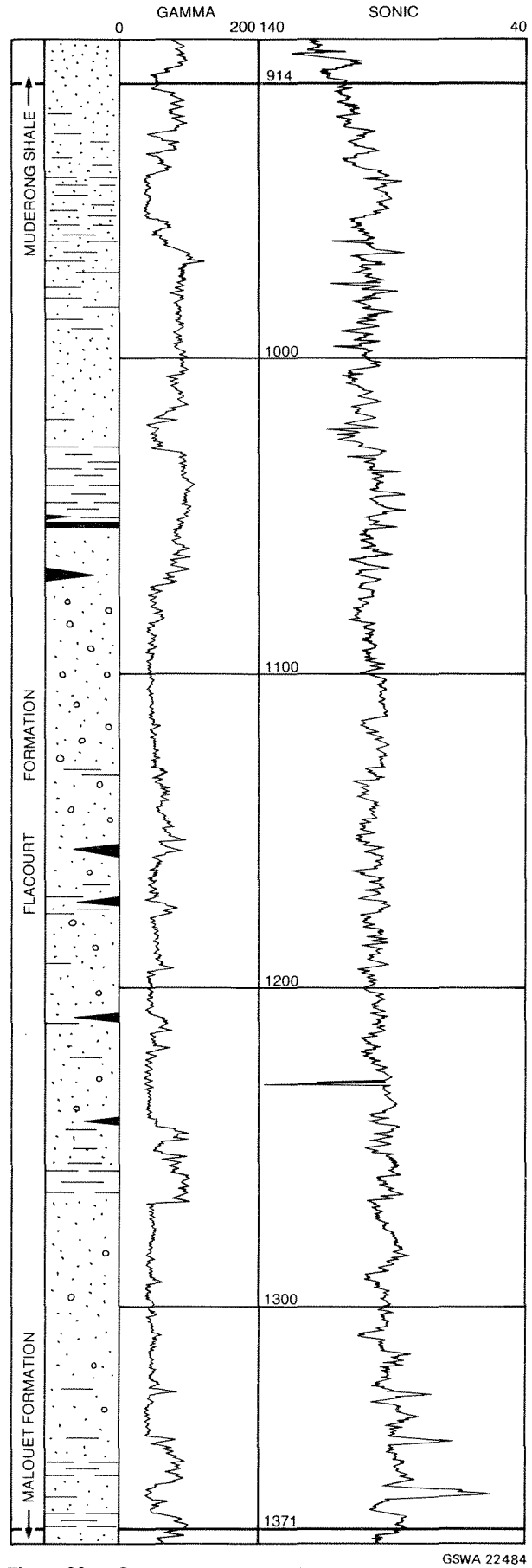

Figure 90. Gamma-ray and sonic logs of Flacourt Formation type section, Barrow 1, 1370–1914 m.

fluvial channels and interchannel areas, through coastal barriers, to shallow-marine distributary mouth bars and associated delta-front environments. Lack of cores has precluded identification of specific environments. The most characteristic deposit is a stacked sequence of sands, usually about 10 m thick, but when shale splits are poorly developed, sand packages up to 125 m thick occur.

UNGROUPED UNITS

WOGATTI SANDSTONE

Definition

The Wogatti Sandstone (McWhae and others, 1958) has been recognized only in the Rough Range area, where it underlies the Birdrong Sandstone and overlies the Learmonth Formation. Johnstone (1979) considered that both contacts are unconformable, whereas Playford and others (1975) and McWhae and others suggested the lower contact is possibly conformable. The type section is in Rough Range 1 between 1109 and 1216 m.

Lithology

The Wogatti Sandstone consists of medium- to coarse-grained, poorly sorted argillaceous sandstone, oxidized pale grey to white, with thin, sharply bounded splits of dark, highly carbonaceous and argillaceous siltstone.

Distribution and thickness

The formation is apparently restricted to a narrow strip along the downthrown side of the Rough Range Fault, except in Whaleback 1. It has been intersected by Learmonth 2, Rough Range South 5, Whaleback 1 and the Rough Range wells. The type section is the thickest intersection.

Fossils and age

The only organic remains are plant debris, which Balme (*in* Playford and others, 1975) considered were probably Neocomian. The Wogatti Sandstone thus correlates with part of the Barrow Group, and may correlate with the Nanutarra Formation or Yarraloola Conglomerate.

Environment of deposition

The lithology, restricted distribution and lack of marine fossils suggest that the Wogatti Sandstone is a fluvial or alluvial-fan deposit, with deposition largely controlled by movement on the Rough Range Fault. It is present in the upthrown block in Whaleback 1, indicating that deposition extended back from the fault locally.

YARRALOOLA CONGLOMERATE

Definition

The Yarraloola Conglomerate (Hoelscher and McKellar, *in* McWhae and others, 1958) extends along the eastern margin of the Carnarvon Basin between the Fortescue and Ashburton Rivers, and is best developed in the Robe River area. It and the Nanutarra Formation form an interrelated fluvial to shallow-marine sequence (Hocking and van de Graaff, 1978). Differentiation of the two units is based solely on grain size: the Yarraloola Conglomerate is a conglomeratic facies with minor sandstone and siltstone, whereas the Nanutarra Formation is a mixed sequence of sandstone and siltstone with minor conglomerate. At the type section, 11 km southeast of Yarraloola homestead, the Yarraloola Conglomerate rests unconformably on Precambrian basement. Elsewhere in the Robe River area, it commonly conformably overlies Nanutarra Formation, and further south on Nanutarra Station it conformably underlies and grades laterally into the Nanutarra Formation. Note that the type section is at 21°37′30″S, 115°57′10″E, and not where Hoelscher and McKellar indicated.

In outcrop, the top of the Yarraloola Conglomerate/Nanutarra Formation sequence is in most places an erosion surface, but in the subsurface the sequence is generally conformably overlain by the Muderong Shale and may grade into the Birdrong Sandstone.

Lithology

The Yarraloola Conglomerate consists predominantly of sandy, pebble- to cobble-sized, polymictic conglomerate grading to pebbly sandstone (Fig. 91). It is medium grey in the subsurface and generally lateritized in outcrop. Sorting is poor and a clay matrix is usually present. Sand grains are angular to subangular, and conglomerate clasts range from angular to well rounded. Clasts include chert, quartz, quartzite, banded-iron-formation and other resistant Precambrian rock types. In the subsurface, glauconite is locally present. Bedding ranges from crude planar bedding to trough and tabular cross-bedding, with numerous scours, fining-upward cycles, sandstone

and pebble lenses, and some rootlet horizons. Ferruginized wood is common, and bivalves have been found in one locality.

Well-sorted, medium- to fine-grained sandstone is locally present where the formation grades laterally into the Birdrong Sandstone, and siltstone interbeds are common throughout.

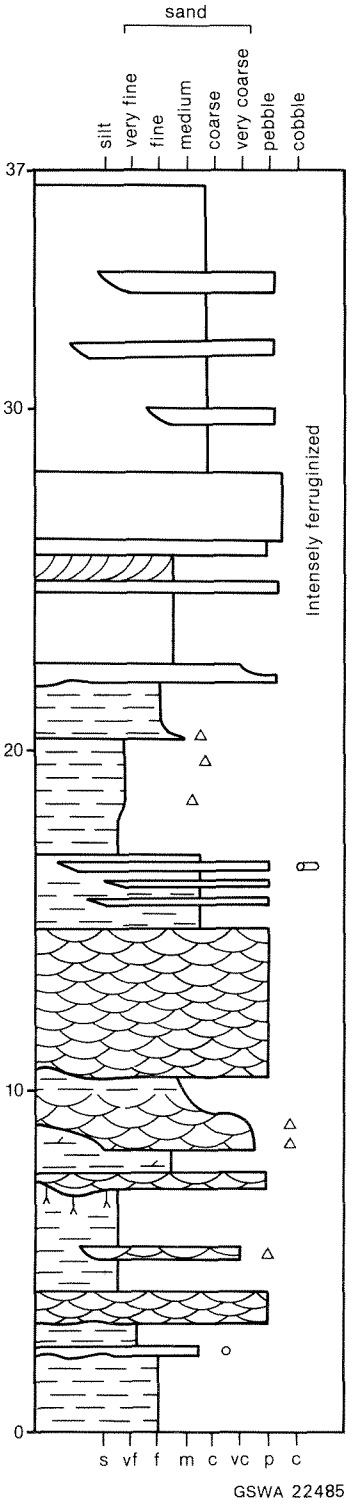

Figure 91. Measured section of Yarraloola Conglomerate near type section, Sugarloaf Hill area, YARRALOOLA.

Distribution and thickness

The main area of outcrop of the Yarraloola Conglomerate is around the Robe River where it was clearly deposited by an ancestral Robe River. Isolated outcrops extend north to the Fortescue River and south to the Ashburton River and Uaroo and Nyang Stations (Fig. 92). In the Peepingee Creek area, poorly exposed pebble to boulder conglomerate, up to about 20 m thick, occurs beneath the Nanutarra Formation in depressions on the basal unconformity. These occurrences are fluvial valley fills of Yarraloola Conglomerate underlying marginal marine Nanutarra Formation. South of The Range homestead, mesas of coarse-grained to pebbly sandstone, mapped as Yarraloola Conglomerate by van de Graaff and others (1980), occur at the same level as mesas of Nanutarra Formation, indicating that the two units are laterally equivalent. The Yarraloola Conglomerate is present under the coastal plain and immediately offshore on YARRALOOLA and eastern ONSLOW. Its thickness is quite variable because of topographic relief at the time of deposition and is generally less than 50 m. Thomas (1978, Fig. 9) compiled an isopach map of the formation showing two distinct trends, perpendicular to each other which he interpreted as a palaeochannel with an offshore barrier or strandline deposit.

Fossils and age

Fossil wood and leaves are common in the formation, and the bivalve *Panopea glaessneri* occurs in life position at 21°39′40″S, 116°03′40″E (YARRALOOLA). The presence of this bivalve and the stratigraphic relationships of the Yarraloola Conglomerate with the Nanutarra Formation, Birdrong Sandstone and Muderong Shale indicate that it is Neocomian (Early Cretaceous), not Jurassic as Walkom (*in* McWhae and others, 1958) suggested after studying the fossil leaves.

Environment of deposition

The Yarraloola Conglomerate is primarily a fluvial deposit, as indicated by the sorting, bedforms, fining-upward cycles and rootlet horizons. There were localized marine incursions, indicated by the presence of glauconite and rare marine fossils. In the subsurface, Thomas (1978) recognized local thick areas which he interpreted as strandline deposits.

GSWA 22486

Figure 92. Yarraloola Conglomerate, south of Deep Well, Uaroo. Angular quartz-boulder breccia in sandy matrix abutting vertically dipping Precambrian. This outcrop is in a Cretaceous palaeovalley filled with Yarraloola Conglomerate.

NANUTARRA FORMATION

Definition

The Nanutarra Formation (Hoelscher and McKellar, *in* McWhae and others, 1958) is a clayey to sandy siliciclastic sequence which has been recognized along the eastern margin of the northern Carnarvon Basin. It is closely related to the Yarraloola Conglomerate and was discussed in some detail by Hocking and van de Graaff (1978). The type section is about 8 km northeast of The Range homestead. On YANREY and WINNING POOL, the Nanutarra Formation rests unconformably on Precambrian basement or conformably on the Yarraloola Conglomerate, and the top is mostly an erosion surface (although locally, the formation is overlain conformably by greensand of the Muderong Shale). The Nanutarra Formation contains the Peepingee Greensand Member, an immature glauconitic sandstone which is present in the Tabletop Hills (YANREY).

A lateral transition from Nanutarra Formation into Windalia Radiolarite can be seen in places, and on YANREY was described by Hocking and van de Graaff (1980). On WINNING POOL, this transition can be seen on Nyang Station between Aermotor Well and Millerin Claypan. Here, the sandstone of the Nanutarra Formation grades westwards into bioturbated siltstone and then into silty Windalia Radiolarite.

Peepingee Greensand Member

This was erected as a formation by Hoelscher and McKellar (*in* McWhae and others, 1958) but Hocking and van de Graaff (1978) reduced it to member status, because of its apparently conformable relationship with the Nanutarra Formation and its restricted distribution. The Tabletop Hills, 37 km northwest of Nanutarra homestead, are the only known outcrops and contain the 11 m thick type section. The member consists of highly glauconitic, fine- to medium-grained, poorly sorted feldspathic sandstone which is much less mature than greensands of the Muderong Shale in nearby areas. The member fills a locally significant scour and formed in a protected nearshore-marine to estuarine area.

Lithology

The Nanutarra Formation consists of interbedded silty sandstone and poorly sorted immature sandstone, commonly with minor pebbly sandstone at the base and some claystone in the upper part. Glauconitic sandstone is present in the Peepingee Greensand Member.

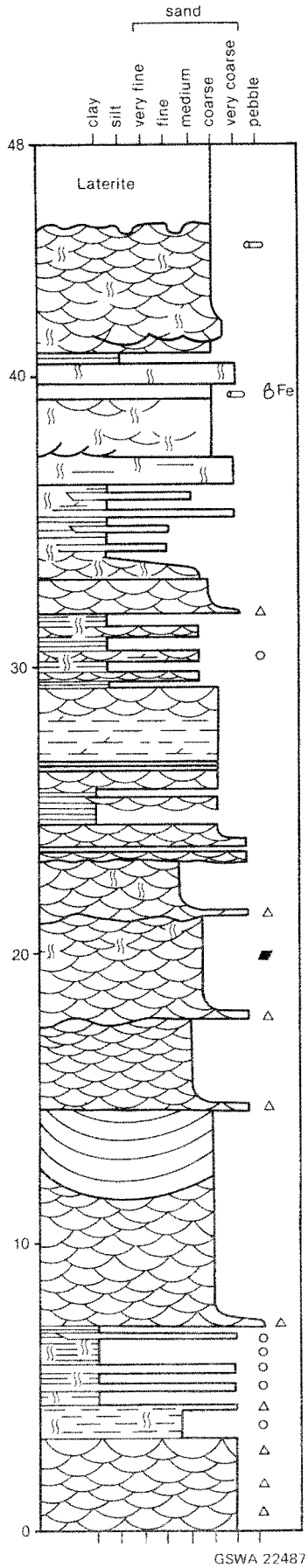

Figure 93. Nanutarra Formation measured section, Jubricoo Creek area. This is section 6 of Hocking and van de Graaff (1978).

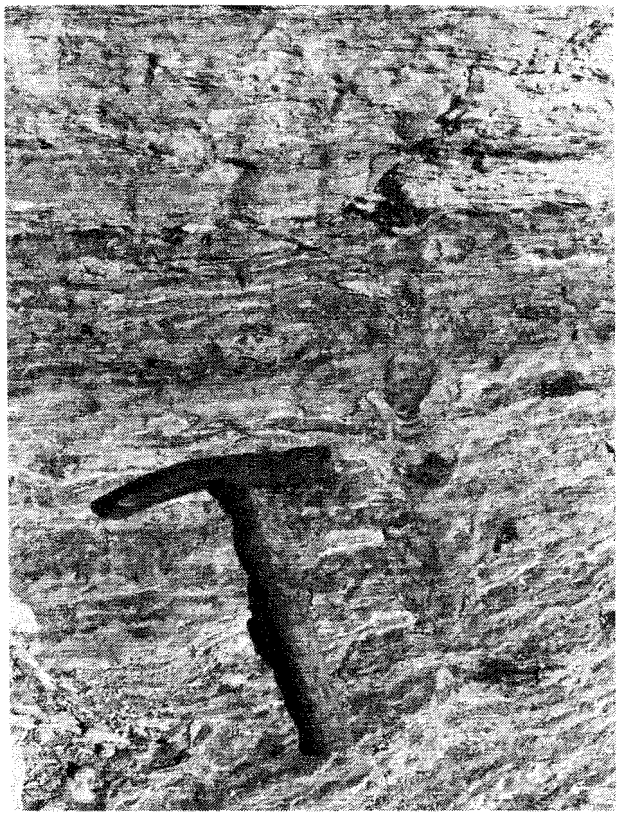

Figure 94. U-shaped burrow and thin wavy bedding in basal Nanutarra Formation, Peepingee Creek area.

The formation is best exposed in a group of mesas between Peepingee and Jubricoo Creeks on Nanutarra Station, where it overlies basement with an irregular unconformity. The unconformity had a local relief of several tens of metres and the deposited thickness is very variable. In some depressions, the Yarraloola Conglomerate conformably underlies the Nanutarra Formation. In the Jubricoo Creek area, the thickest section measured is about 45 m thick (Fig. 93). It consists of a 7.5 m thick basal unit of pebbly, poorly sorted, cross-bedded sandstone with intense bioturbation in the upper part (Fig. 94). This is overlain by 16.5 m of cross-bedded, well-sorted sandstone which grades up into 12 m of interbedded siltstone and sandstone. This in turn grades up into partly gritty, medium-bedded sandstone. This upper unit contains abundant burrows and a ferruginized bed which is richly fossiliferous with numerous bivalves (*Panopea glaessneri*), mostly in life position. This intensely ferruginized horizon may have originally been calcareous. The sandstones are generally compositionally immature, with angular to subangular grains dominant. Although lateral facies changes do occur, a similar sequence is recognizable in most sections in this area (Hocking and van de Graaff, 1978, Figs 17 and 18).

GSWA 22489

Figure 95. Rootlet horizon in Nanutarra Formation south of Deep Well, Uaroo. Lens cap is 53 mm in diameter.

In isolated outcrops, recognition of the Nanutarra Formation and its differentiation from the Birdrong Sandstone is based on the immaturity and variability of the Nanutarra Formation compared to the Birdrong Sandstone.

Subaerial exposure during deposition is indicated by the local development of soil horizons and the presence of rootlets (Fig. 95).

Distribution and thickness

The formation outcrops along the eastern margin of the Carnarvon Basin between the Tanpool Hills and the Minilya River, and isolated mesas occur for some distance into the Precambrian hinterland. It has not been recognized in the subsurface, where most basal Cretaceous sands are described as Birdrong Sandstone.

Because of the uneven underlying topography the Nanutarra Formation varies greatly in thickness. The thickest measured section is 45 m, but it probably exceeds 50 m in thickness immediately adjacent to Peepingee Well. The thickness of the type section, 25 m, is typical of outcrops away from the Jubricoo Creek–Peepingee Creek area.

Fossils and age

Fossils are locally abundant in the Nanutarra Formation, and include bivalves, gastropods, belemnites, corals, ferruginized wood, and plant leaves. Their occurrence ranges from isolated specimens to both autochthonous and allochthonous concentrations. Some of the fossil wood has *Teredo* borings. Cox (1961) described the molluscan fauna and suggested an Early Cretaceous age, which Skwarko (1966) supported, refining the age to Late Neocomian to Aptian. Plant fossils had previously been considered by Walkom (*in* McWhae and others, 1958) to indicate a Late Jurassic age.

The apparent lateral equivalence of the Nanutarra Formation to the Birdrong Sandstone, Muderong Shale and Windalia Radiolarite suggests that it ranges in age from mid-Neocomian (the age of the Birdrong Sandstone, which the Nanutarra Formation certainly underlies in places) to the Albian-Aptian boundary (the age of the Windalia Radiolarite). As the identification of the Nanutarra Formation is based on the recognition of sandy basin-marginal facies, it may be markedly diachronous. Also, there may be numerous unrecognized small disconformities (not generally obvious in outcrop) within the formation.

Environment of deposition

The Nanutarra Formation is a marginal marine deposit which formed in, and adjacent to, a drowned ria coastline, and was protected from major marine reworking by an incomplete barrier of Precambrian islands. The amount of sediment brought into the basin was not great, resulting in a condensed sequence. This formed mainly in restricted nearshore to tidal and supratidal conditions. Fluvial deposition occurred near the hinterland and at times of greater input.

WINNING GROUP

The Winning Group ("Winning Series" of Raggatt, 1936; amended by Fairbridge, 1953b) consists of the Birdrong Sandstone, Muderong Shale, Windalia Radiolarite, Gearle Siltstone, Alinga Formation, and Haycock Marl.

Early definitions (*e.g.* Condon and others, 1956; Johnstone and others, 1958) were based on onshore geology, where the group is a readily recognizable, unconformity-bound, siliceous sequence. However, the bounding unconformities are not present in much of the northern, offshore Carnarvon Basin, and the lithology changes to a mixed-carbonate and siliceous sequence.

The Winning Group was deposited during a major transgression which began in the Neocomian and continued through the Cretaceous. In most areas, a diachronous basal transgressive sand—the Birdrong Sandstone—formed at the onset of the transgression. In the wake of the transgression, there was low-energy offshore-marine deposition, forming the Muderong Shale. Continued high sea levels, "tropical" deep weathering, and possibly excess dissolved silica in the ocean (as a result of submarine volcanism along newly-active spreading centres) led to substantial siliceous pelagic deposition. This formed the Windalia Radiolarite and parts of the Gearle Siltstone. In the outer parts of the Barrow and Dampier Sub-basins there was virtually no terrigenous supply, and limestones formed between radiolarite phases. The uppermost part of the Winning Group is variable: south of Shark Bay, glauconitic siltstone and greensand (Alinga Formation) were deposited; between Shark Bay and the Dampier Sub-basin, bentonitic siltstone and claystone (Gearle Siltstone) were deposited; and in the Dampier Sub-basin, calcareous marl (Haycock Marl) was deposited. Deposition of the Winning Group was terminated by the basin-wide change to the calcareous pelagic deposition of the Toolonga Calcilutite.

BIRDRONG SANDSTONE

Definition

The Birdrong Sandstone (Condon, 1954; amended by Playford and others, 1975) is a unit of quartzose, commonly glauconitic and friable, sandstone and silty sandstone at the base of the Winning Group. It is conformably overlain by the Muderong Shale or (in the southern Carnarvon Basin) the Windalia Radiolarite. Synonymous names for the unit are "Tutula Sandstone" and "Butte Sandstone". "Tutula Sandstone" has priority over Birdrong Sandstone, but the latter is sufficiently entrenched in the literature that a formal change would be pointless. The type section (Fig. 96) is on the western side of Kennedy Range, about 1 km southwest of Birdrong Spring. It unconformably overlies older sediments, except where the Wogatti Sandstone or Nanutarra Formation is present. Thomas (1978) reduced the Birdrong Sandstone to member status in the Barrow Sub-basin area, but this is not accepted here. The Grierson Member was created by McWhae and others (1958) for a silty facies at the base of the Birdrong Sandstone in the Lake MacLeod area.

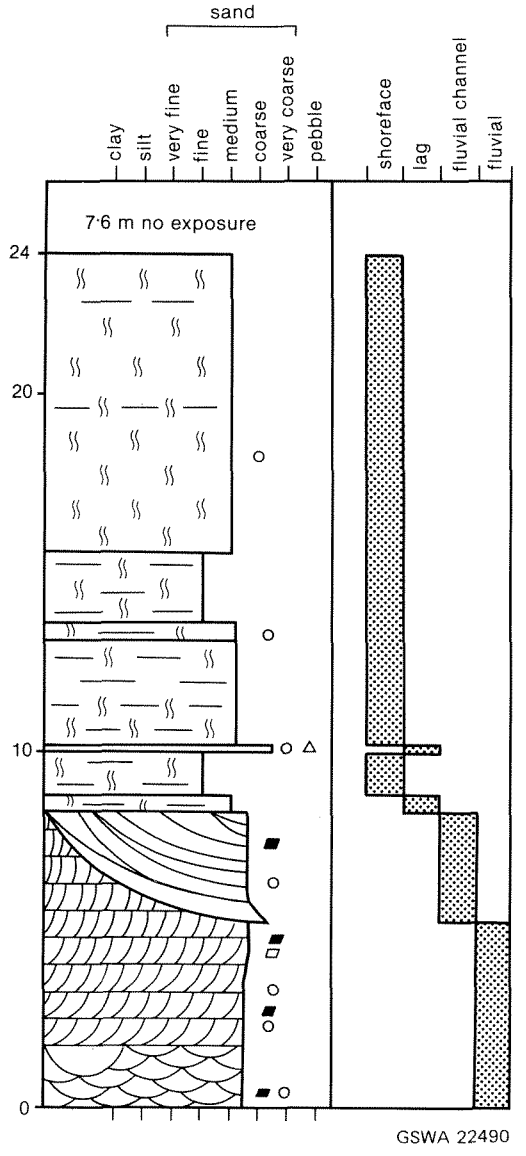

Figure 96. Birdrong Sandstone type section, near Birdrong Spring. Large scour at 6–8 m may represent base of transgression and be of regional significance.

Grierson Member

This consists of 29 m of interbedded carbonaceous siltstone and glauconitic sandstone, and is present at the base of the Birdrong Sandstone in the Grierson wells on the Grierson Anticline. Similar sediments occur in water bores in the southern Carnarvon Basin (McWhae and others, 1958; see also the section on the Woodleigh Formation). They represent a locally developed facies, which accumulated in topographic lows at the onset of the transgression.

Lithology

Two main facies are present in outcrop. The principal facies is a fine- to coarse-grained, moderately well-sorted, relatively featureless, quartz sandstone. It is commonly silty (to a variable degree) and glauconitic. Bedding features are not well preserved due to extensive bioturbation and the friable nature of the unit, although pebble stringers and gross bedding can locally be distinguished. The colour ranges from grey or greyish green to oxidized yellow and brown.

The second facies in outcrop is small- to medium-scale, cross-bedded, fine- to very coarse-grained sandstone, locally silty and pebbly, and poorly to moderately sorted. Neither glauconite nor bioturbation are present. This facies has been found at a few localities at the base of the unit (*e.g.* the bottom eight metres of the type section, Fig. 96). Palaeocurrent data are westwards to northwards. This facies presumably grades westwards into the facies represented by the Grierson Member.

The Birdrong Sandstone is commonly very friable in outcrop, and locally could be mistaken for Cainozoic superficial sand except for its stratigraphic position. In the easternmost outcrops, it is distinguished from the Nanutarra Formation, which it overlies and grades laterally into, by its generally better sorting and (commonly) the presence of glauconite.

In the subsurface, the Birdrong Sandstone is a pale-grey to white, locally greenish, glauconitic sandstone and greensand. Bedding ranges from thin planar-bedded units to tabular and trough cross-stratified units. Siltstone beds occur, locally grading into silty claystone and shale.

Distribution and thickness

The Birdrong Sandstone extends from the Murchison River in the south to (at least) Hampton 1 in the north. Towards the basin margin, it grades into the Nanutarra Formation north of the Minilya River. Further south, the easternmost outcrops have been removed by erosion or are covered by sandplain. It was not deposited in the outer Barrow and Dampier Sub-basins nor in isolated areas which were topographically high throughout the Neocomian, such as the Yanrey High and beneath Cape Range. Greater than average thicknesses of sandstone accumulated in topographic lows, such as between Glenroy 1 and Minderoo 1, and around East Marrilla 1.

The Birdrong Sandstone is mostly 20 to 30 m thick, with a maximum known thickness of 64 m in East Marrilla 1. Other notably thick intersections are in Enderby 1 (55 m) and Hampton 1 (57 m). The thickness of "200 feet" given by Condon (1968) for outcrops in the Murchison River area is incorrect: the sequence is 30 to 35 m thick there. In Rough Range 1, the Birdrong Sandstone is only 11 m thick, not 118 m as stated by Condon (1968).

Fossils and age

The most useful fossils for dating the Birdrong Sandstone are marine microplankton and terrestrial spores and pollen. These are sparse, poorly preserved and are often contaminated by material reworked from older sediments. Molluscs and fossil wood (with infilled *Teredo* borings) are also present.

Deposition of the Birdrong Sandstone began in the northwestern part of the Carnarvon Basin, and proceeded southwards and eastwards. Wiseman (1979) considered that the Birdrong Sandstone is almost wholly Neocomian, with deposition beginning in the early Hauterivian to late Valanginian, and continuing at least to the Barremian in the Barrow Sub-basin. In the southern Gascoyne Sub-basin, the Windalia Radiolarite rests conformably on the Birdrong Sandstone, with no intervening Muderong Shale, suggesting that there the Birdrong Sandstone extends into the Aptian.

Environment of deposition

The Birdrong Sandstone is primarily a coastal to nearshore deposit which formed as the Neocomian transgression proceeded. It is markedly diachronous, as shown by Wiseman (1979). The dominant, bioturbated-sandstone facies was deposited on the lower shoreface. Sediment supply for the Birdrong Sandstone came partly from reworking of residual material and partly from reworking of contemporaneously supplied terrigenous detritus. The generally intense

bioturbation indicates that energy levels and supply rates were low to moderate rather than high.

The lower, cross-stratified facies is probably a fluvial deposit which was deposited prior to the transgression. In most areas, pre-existing unconsolidated sediments were totally reworked and incorporated into the bioturbated facies or, if fine grained, into the offshore lateral equivalent, the Muderong Shale. Fluvial deposits were preserved in isolated hollows and otherwise protected areas.

The Grierson Member is probably a swampy coastal deposit, which formed in hollows and protected areas prior to and during sea-level rise. The finer grained parts of the member are back-barrier lagoonal-marsh deposits, while the sands are washover fans and tidal deltas.

Economic aspects

The Birdrong Sandstone is significant as an aquifer and a petroleum reservoir. It is the reservoir for the Rough Range oil accumulation, and at least a secondary objective for any exploratory well intersecting it within closure. It is also the most common artesian and subartesian aquifer (generally only for stock-quality water) in the Carnarvon Basin.

MUDERONG SHALE

Definition

The Muderong Shale (Condon, 1954) is the argillaceous sequence which lies conformably between the Birdrong Sandstone and Windalia Radiolarite. Where the Birdrong Sandstone is absent, the Muderong Shale rests conformably on the Barrow Group or unconformably on older rocks. In the subsurface, the Muderong Shale and Windalia Radiolarite are commonly indistinguishable on lithological grounds. The type section is about 2 km southwest of Twins (Muderong) Bore on Middalya Station.

Two members are present in the shale, all with limited areal extent. These are the Mardie Greensand Member at the base, and the Windalia Sand Member at the top. The name "Windalia Sand Member" is invalid on formal stratigraphic grounds, since it is pre-empted by the Windalia Radiolarite. However, both names are so thoroughly entrenched in the literature that any proposed change in nomenclature would be ignored by future workers.

Mardie Greensand Member

This member was named by Thomas (1978) and defined by Lowry (*in* Wiseman, 1979). It includes the "Muderong Greensand Member" of Crank (1973) and Thomas and Smith (1976). The type section is in Mardie 1, between 160 and 172 m. It is transitional between the Birdrong Sandstone and Muderong Shale, and consists of dark-green, glauconitic, sandy siltstone, interbedded with dark-grey siltstone and shale. The glauconite comprises up to 60% of the rock (Thomas, 1978), usually in the form of pellets, but also as a matrix. Quartz silt and sand are commonly entirely absent.

The Mardie Greensand Member is commonly 10 to 20 m thick, with a maximum of 40 m. As boundaries are gradational, estimates are subjective. The member extends over the Peedamullah Shelf, along the eastern margin of the Barrow and Dampier Sub-basins, and into the Barrow Sub-basin at least as far as Barrow Island. It is highly diachronous, ranging in age from Valanginian to Aptian (Wiseman, 1979).

Oil has been produced from the Mardie Greensand Member on Barrow Island, though it is not a major reservoir. In this area it is divided into two units, 5.5 m and 3 m thick, of fine- to medium-grained silty greensand, separated by an impermeable argillaceous and calcareous zone.

Windalia Sand Member

This unit was initially thought to occur within the Windalia Radiolarite (Parry, 1967), but is now recognized as belonging in the upper part of the Muderong Shale (Crank, 1973; Campbell and others, 1984). The name, although formally invalid, is here retained because it is too entrenched in the literature to consider changing. The member is a facies variant of the uppermost Muderong Shale and is conformably overlain by the Windalia Radiolarite. The type section is in Barrow 1 between 644 and 674.5 m.

The Windalia Sand Member consists of very fine- to fine-grained, moderately sorted sandstone with lesser siltstone, shale, and thin calcareous lenses. Lateral facies changes are rapid and numerous, resulting in large variations in the section. A shale bed, 6 m thick, persists across the whole of Barrow Island and separates upper (average 16 m thick) and lower (average 10 m thick) sand units. The colour of the member ranges from greenish grey (when glauconite is present) to pale or medium grey. Lithological changes are generally gradational rather than abrupt.

The member is known from Barrow Island and the Robe River area, and may be present in Giralia 1. At Barrow Island it has an average thickness of 37 m, and varies by about 8 m across the field (Williams, 1977). In the Robe River area the sand development is weakly expressed and not as laterally persistent. In Giralia 1, a well-sorted, fine-grained, glauconitic sandstone in the upper part of the Muderong Shale may be the Windalia Sand Member.

The member probably formed on topographically higher areas during a slight drop in sea level, by wave-caused winnowing of underlying sediment in the virtually starved basin (Williams, 1977). The starvation of the basin is illustrated by the presence of carbonate-rich lenses in the unit. An unconformity represents this stratigraphic interval in the Dampier Sub-basin.

Lithology

Although named the Muderong Shale, the unit is dominantly an argillaceous siltstone. Thin lenses of pure siltstone and fine sandstone (possibly resembling shale) are common. It is usually medium to dark grey, grading to grey-green when glauconitic, and grey-brown when the organic content is high. Most exposures show intense bioturbation. Glauconite is a common accessory, and the formation locally consists of relatively pure (free of quartz sand and grit) greensand, as at Nanyingee Hill and near Sugarloaf Hill (Towera Station). Pyrite occurs as nodules, stringers or (in coarser lithologies) cement, and mica is locally noticeable in highly quartzose siltstone. Siltstone is generally slightly calcareous, and thin beds of fine-grained, dolomitized brown limestone are common. The carbonate content increases offshore, and in the Dampier Sub-basin the formation is uniformly calcareous.

Distribution and thickness

The Muderong Shale is generally readily distinguished from the Windalia Radiolarite in outcrop because of the distinctive outcrop pattern of the latter, but in the subsurface the lithological difference is commonly slight. Disconformities mark the top and base of the unit in the Dampier Sub-basin.

Onshore, the Muderong Shale is mostly 10 to 20 m thick, thinning and (commonly) coarsening to a greensand near the basin margin. It was not deposited south of (approximately) the Gascoyne River. Some topographic highs remained exposed during deposition of the shale, such as the Yanrey High and the Cape Range area (Wiseman, 1979, Fig. 9).

In the offshore sub-basins, the Muderong Shale has only minor discontinuities, and varies in thickness from about 10 m on high blocks of the northern Rankin Platform (*e.g.* North Rankin Field, Eaglehawk 1) to 300 m or more in basin depocentres. Seismic correlation suggests that the thickness of the Muderong Shale may exceed 1000 m, north of Barrow Island (Johnstone and others, 1976).

Fossils and age

Macrofossils are rare in the Muderong Shale, but microfossils are abundant and allow precise dating (*e.g.* Wiseman, 1979). Imprints of wood are locally present in outcrop, and bioturbation is generally intense.

The formation is markedly diachronous: the base ranges from Valanginian in the northernmost parts of the basin to Aptian in southerly areas. The top of the formation is late Aptian, and less diachronous.

Environment of deposition

The Muderong Shale was deposited in a low-energy, offshore-marine environment, in the wake of the Neocomian transgression. The base of the unit is thus diachronous. The palaeogeographic reconstructions of Wiseman (1979) show a progression from relatively restricted marine conditions in the Valanginian to open-marine conditions in the early Aptian. In shallower areas, such as near the basin margin and over structurally induced topographic highs (*e.g.* Yanrey High, Barrow Island area) energy levels were higher, and finer sediments were winnowed out, leaving greensands and other slightly coarser grained sediments to form the Mardie Greensand Member and Windalia Sand Member.

Economic aspects

The Muderong Shale is the seal for the gas/condensate accumulations of the Rankin Platform and Dampier Sub-basin. In Barrow Island, it acts as a seal to some minor oil accumulations, but the principal field is within the Windalia Sand Member at the top of the Muderong Shale. The formation also seals the accumulations at Rough Range and Tubridgi. The Mardie Greensand Member also contains some hydrocarbons, in Barrow Island and the Robe River area.

WINDALIA RADIOLARITE

Definition

The Windalia Radiolarite was named by Condon (1954) and defined by Condon and others (1956). The name is a junior synonym of Thirindine Formation ("Thirindine Shale" of Clarke and Teichert, 1948; amended by Johnstone and others, 1958) but, as with Birdrong Sandstone and "Tutula Sandstone", the later name has become too firmly established for it to be abandoned.

The Windalia Radiolarite rests conformably in the Muderong Shale or the Birdrong Sandstone, except in the Dampier Sub-basin, where it is unconformable on the Muderong Shale. At the basin margin, it appears to grade laterally into Nanutarra Formation. It is conformably overlain by the Gearle Siltstone or (in the south) the Alinga Formation or (in the Dampier Sub-basin) the Haycock Marl. The 36 m thick type section is at Windalia Hill, on Winning Station, and has an eroded top and a poorly exposed base. Most of the formation is moderately to well exposed in the reference section in the Giralia Anticline established by Condon and others (1956). The only stratigraphically complete well-exposed sections are north of Kalbarri on the edge of the Pillawarra Plateau, the type area of the "Thirindine Formation". The interval between 2738 and 2749 m in Goodwyn 6 is a reference section for the Dampier Sub-basin, where the Windalia Radiolarite shows distinct lithological differences.

Lithology

The Windalia Radiolarite in outcrop is a uniform white-weathering, radiolarian siltstone, commonly with a low specific gravity. Except for poorly expressed blocky bedding, bedding structures are rare. Bioturbation can be detected locally, as can a suggestion of ripple lamination. It commonly has a porcellanized, cherty appearance due to secondary silicification during silcretization, and exhibits liesegang banding (Fig. 97) and blotchy iron staining. While dominantly white, colouration locally varies from yellow to red, purple and brown, depending on the oxidation state of iron.

In the subsurface, the Windalia Radiolarite is medium to dark grey, ranging to grey-brown when carbonaceous and green-grey or olive black when glauconitic. The content of radiolarians ranges from about 5% to (uncommonly) 70%. Scattered quartz grains, deposited from suspension, locally are sufficiently abundant and coarse to form an argillaceous sandstone, commonly with siderite cement. Pyrite and small spheres of bentonite are common accessories. The sequence is usually well laminated, and shows persistent bedding on a decimetre to metre scale.

The unit is commonly calcarerous, and calcareous nodules or lenses occur throughout the section. In several water bores in the Shark Bay area, there are beds up to 70 cm thick of black to dark-grey conchoidally fracturing chert. These probably resulted from partial solution and redeposition of silica by percolating groundwater during diagensis.

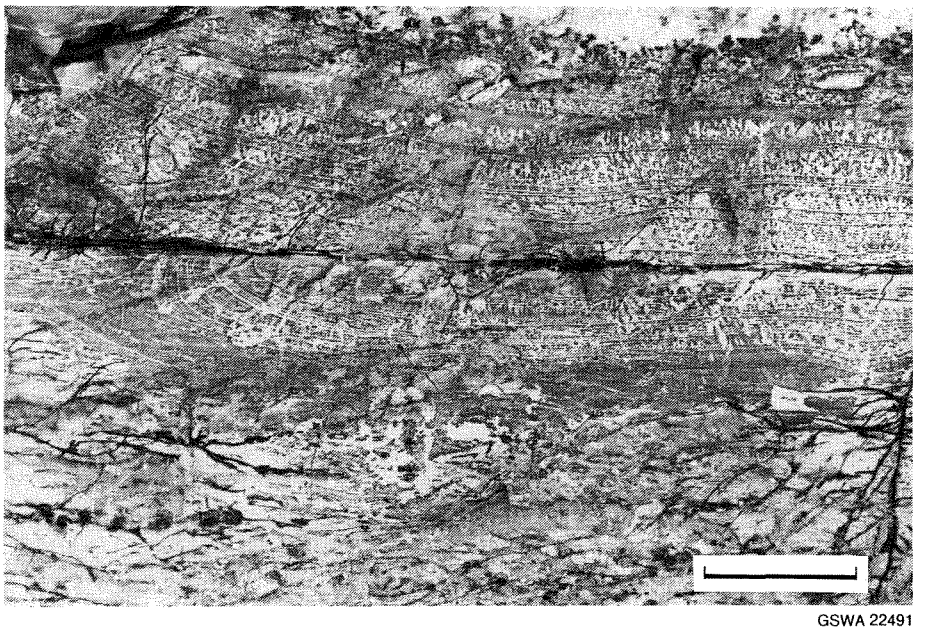

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Figure 97. Windalia Radiolarite near type section showing prominent liesegang banding and patterns. This locally highlights burrows, and is typical of unit. Scale bar 20 cm.

Heath and Apthorpe (written comm.) state that, in most of the Dampier Sub-basin, "the Windalia Radiolarite consists of white to bluish-white, hard calcilutite with common radiolaria and planktonic foraminifera. A thin, basal calcareous claystone to marl is present in some wells. The lower boundary is marked by prominent shifts in neutron porosity and bulk density, and by gamma-ray and sonic logs. The upper boundary is best recognized by the neutron porosity and bulk density logs and to a lesser extent by an inflection in the gamma-ray log" (Fig. 100).

Distribution and thickness

The Windalia Radiolarite is distinctive and easily recognized in outcrop, but in the subsurface it is commonly very similar to both the Muderong Shale and the Gearle Siltstone. Radiolarians are not confined to the Windalia Radiolarite, and are less abundant in offshore areas.

The formation extends over virtually all the Carnarvon Basin. As with most other Cretaceous units, it thickens to the north, from about 12 m in the Murchison River area to 40 or 50 m in most onshore areas, and about 70 m average in the Barrow Sub-basin. In the latter, the thickness is greatest in the central part of the basin, decreasing towards the flanks and over structurally high parts of the basin (*e.g.* where the Windalia Sand Member is present). The Windalia Radiolarite is only about 10 m at Barrow Island, and is thin between Barrow Island and the Robe Riber. The formation is also thin in the general area of the Long Island Fault, suggesting that it may have been high during the Albian.

In the Dampier Sub-basin, Heath and Apthorpe (written comm.) supplied the following information:

"The calcilutite facies of the Windalia Radiolarite extends at least as far north as Delambre 1 (2278–2286 m) and Brigadier 1 (2804–2811 m). Along the Rankin Platform, thicknesses vary from 5 m (North Rankin 5; 2666–2671 m) to 31 m (Lambert 1; 2787–2808 m). The same facies extends as far south as Withnell 1, where it occurs between 2325 and 2336 metres.

"In wells on the eastern side of the basin, the equivalent stratigraphic interval consists of sandstone and siltstone (in De Grey 1 and Hauy 1) and of radiolarian shale (in Rosemary 1, Rosemary North 1, Lewis 1A, Enderby 1, and Hampton 1). Because the overlying and underlying formations in these wells are also shale, there has been no attempt made to separate the Windalia correlative, based on lithology or log characteristics, from surrounding units."

In the Murchison River gorge, the Windalia Radiolarite has been tentatively recognized within the gorge as far upstream as the Z Bend, at a lower topographic level than the uppermost Tumblagooda Sandstone. This indicates that a drainage depression was present along part, or all, of the course of the gorge as early as the Cretaceous.

Fossils and age

Radiolarians and foraminifers are common but poorly preserved, and they have not been studied in detail. The macrofauna includes ammonites, belemnites and bivalves (Fig. 98). Microplankton, ostracods, spors and pollen have also been used in dating. The formation straddles the Albian-Aptian boundary.

In the Dampier Sub-basin, Heath and Apthorpe (written comm.) note: "the only planktonic foraminifera present are long-ranging species of *Hedbergella*, which could be of either Albian or Late Aptian age. The limestone is almost always palynologically barren, but palynological evidence indicates that the basal claystone is of the same age as the Windalia Radiolarite as developed in the Barrow Sub-basin (Wiseman, 1979 and pers. comm.). The palynological zones present (*Diconodinium davidii* and *Muderongia tetracantha* zones of Helby and others, 1987) are of either latest Aptian or early Albian age."

Environment of deposition

The Windalia Radiolarite is a shallow-marine deposit in onshore areas. This is indicated by stratigraphic relationhips between the Windalia Radiolarite and the Birdrong Sandstone (on AJANA) and the Nanutarra Formation (on YANREY and WINNING POOL), and the fact that locally it rests directly on crystalline basement (on the Yanrey High and in a few localities near the Pleiades Hills on WINNING POOL). The presence of silt-size quartz grains and possible ripple lamination suggests that deposition took place just below wave base in at least some areas. Pyrite is present, but only in small amounts, which argues against highly reducing conditions.

The calcilutite facies present in the outer Dampier Sub-basin marks the beginning of open-marine circulation and the commencement of widespread carbonate deposition in that area. The dominantly planktonic nature of the foraminiferal

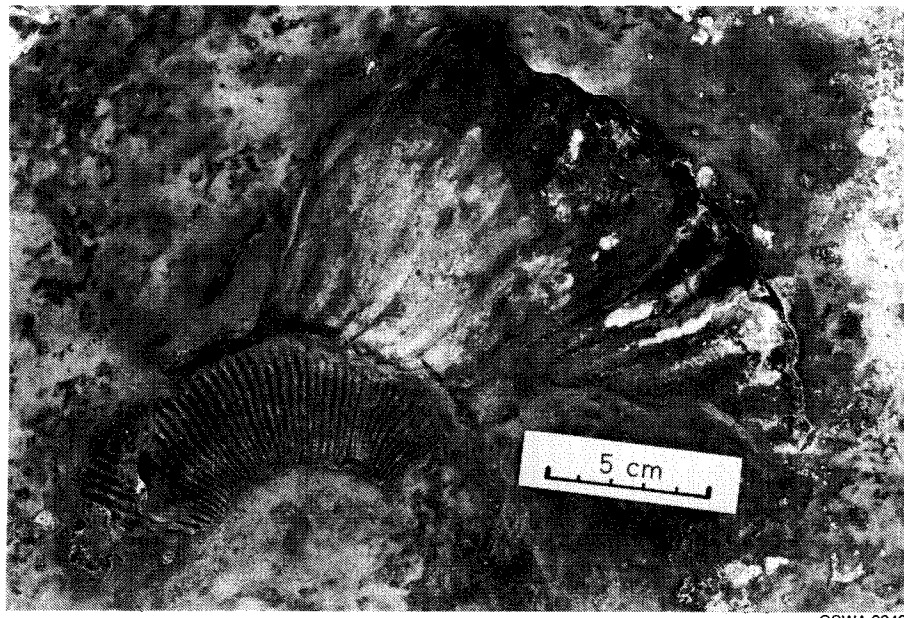

Figure 98. Partial impression of large ammonoid, Windalia Radiolarite type section.

fauna suggests outer-shelf to shelf-edge depths on the Rankin Platform, in contrast to the inner shelf conditions of the onshore Carnarvon Basin. The claystone and siltstone in the southern and eastern Dampier Sub-basin contain benthonic foraminiferal assemblages, suggesting lesser water depths.

The derivation of the dissolved silica, necessary for deposition of the Windalia Radiolarite, is uncertain. In the Carnarvon Basin, basalts being extruded on the mid-oceanic ridge developing to the northwest could have provided excess silica. But elsewhere, as in the Officer Basin where a correlative — the Bejah Claystone — is present (Jackson and van de Graaff, 1981), this mechanism may be invalid. Deep weathering of onshore areas may have provided a source of dissolved silica (to feed radiolarian blooms) and clay (to inhibit calcareous fauna) allowing siliceous rather than calcareous pelagic deposition, with negligible coarse-grained clastic input. This is broadly similar to a mechanism proposed by Folk (*in* McBride and Folk, 1979) to explain Italian Jurassic radiolarites.

HAYCOCK MARL

(R. S. Heath and M. C. Apthorpe)

Definition

The Haycock Marl (Heath and Apthorpe, 1984) is a lateral, more calcareous, equivalent of the Gearle Siltstone in the Dampier Sub-basin and is conformable between the Windalia Radiolarite and Toolonga Calcilutite (Fig. 99). The boundaries are marked by lithological changes which show as character changes in the gamma-ray and density/porosity logs. The marl is distinguished from the Toolonga Calcilutite by its argillaceous content. The type section is in Goodwyn 6 between 2642 and 2738 m and is shown in Figure 100.

Lithology

The Haycock Marl consists of two units of argillaceous calcilutite and marl, separated by a thin, laterally persistent, claystone interval. The lower unit, from 2687.5 to 2738 m in the type section, consists of soft to moderately hard, olive-grey to greenish-grey marl and argillaceous calcilutite. It contains abundant planktonic forminifers, common radiolarians and traces of pyrite.

The central claystone horizon occurs between 2686 and 2687.5 m in Goodwyn 6, and consists of non-calcareous, dark-green to grey claystone with arenaceous benthonic forminifers and recrystallized siliceous spheres which may be radiolarians. It forms a marker horizon within the Haycock Marl, and is typified by a strong response on the gamma-ray and sonic logs.

The upper unit, between 2642 and 2686 m in Goodwyn 6, consists of hard, grey to greyish-green argillaceous calcilutite and marl containing abundant planktonic foraminifers, and minor hard bluish-white calcilutite. In Haycock 1, two intervals of light-grey to greenish-grey, fine- to very fine-grained, well-sorted, variably porous and silty, quartz sandstone, 5 m and 12 m thick, occur in this unit. The sandstone contains 10 to 25%

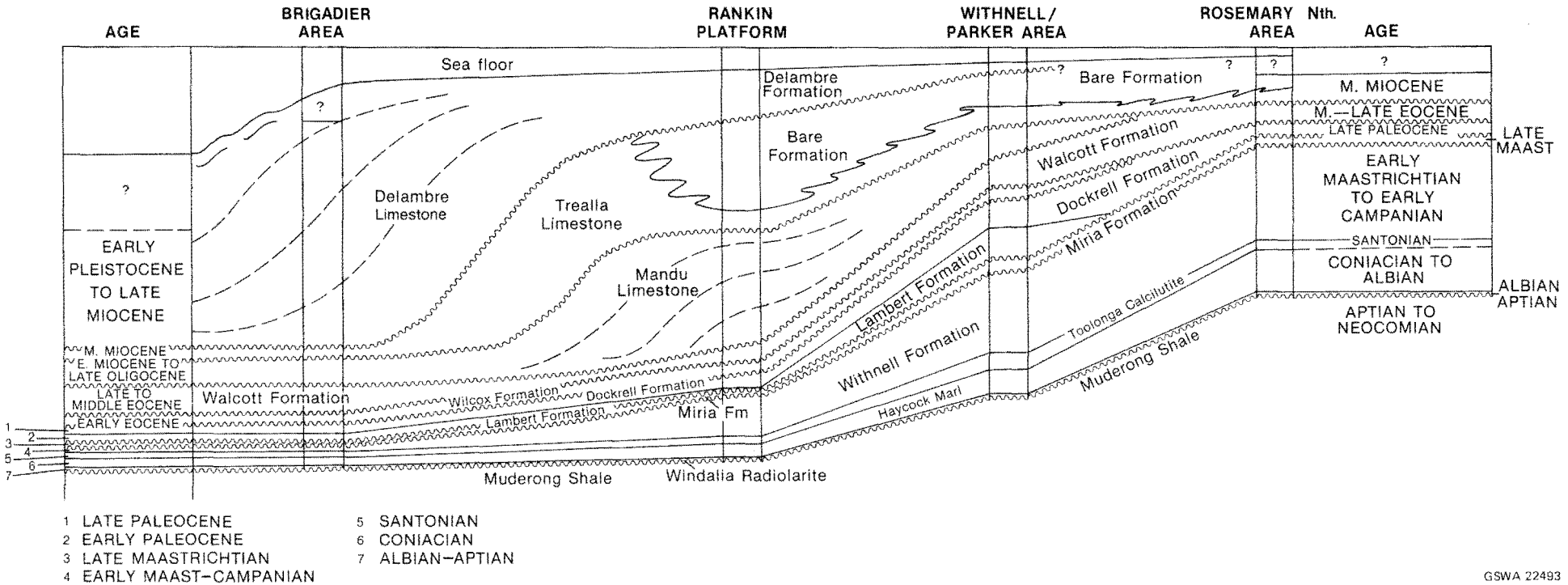

Figure 99. Diagrammatic cross-section over North West Shelf in Dampier Sub-basin area showing stratigraphic units and relationships.

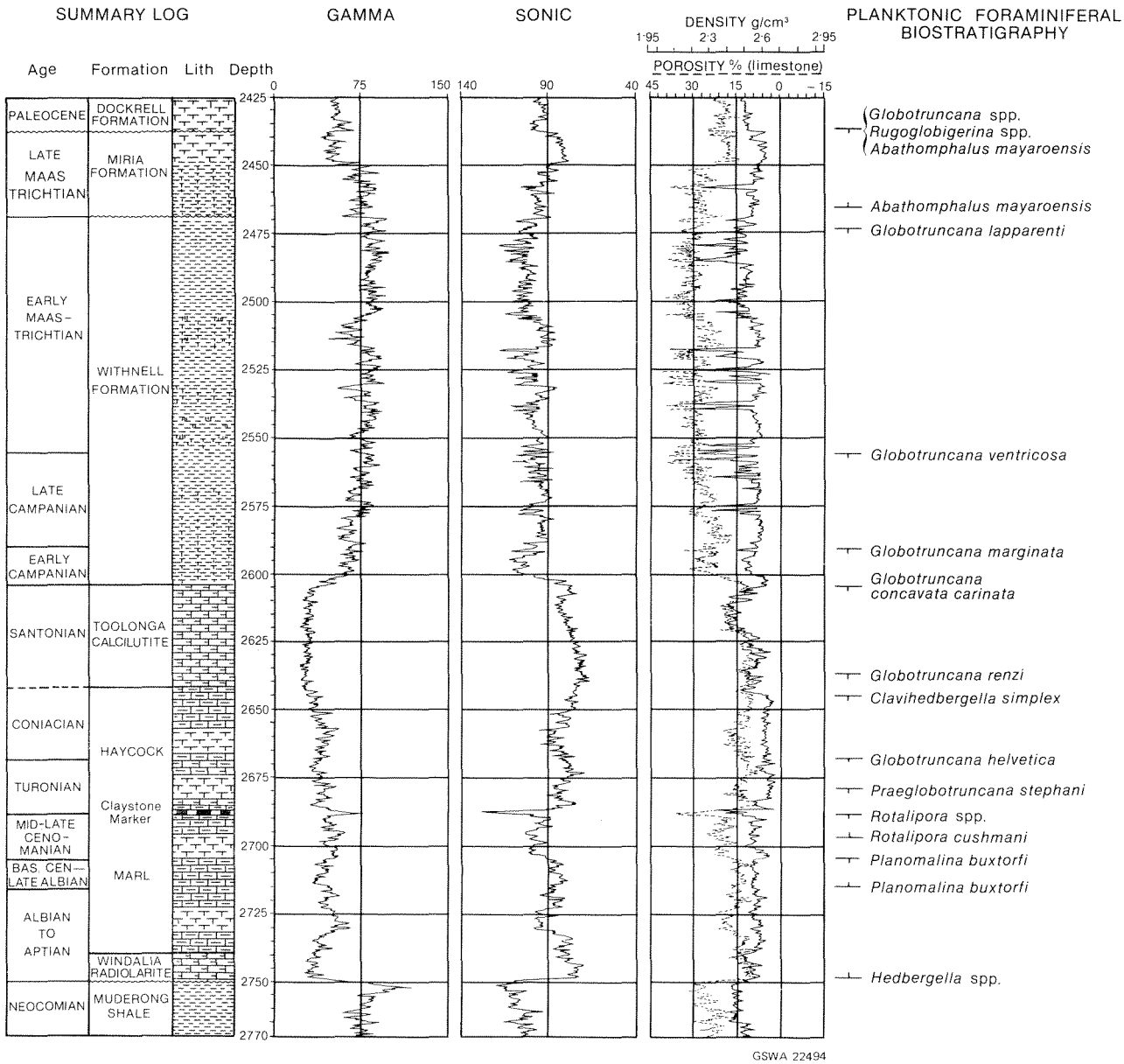

Figure 100. Haycock Marl and Withnell Formation type sections, Goodwyn 6. Windalia Radiolarite, Toolonga Calcilutite and Miria Formation sections are reference sections for Rankin Trend area.

micrite, up to 15% calcite cement, and up to 10% glauconite. Planktonic foraminifers are common within the sandstone, and are mostly aligned along bedding planes, indicating current activity and sorting.

Distribution and thickness

The Haycock Marl occurs in the northwestern part of the Dampier Sub-basin from Delambre 1 to the Rankin Platform. Some typical thicknesses of the Haycock Marl are: Withnell 1, 2171–2325 m (154 m); Haycock 1, approx. 2850–3091 m (approx. 241 m); Miller 1, 2788–2880 m (92 m); North Rankin 5, approx. 2623–2667 m (approx. 44 m); and Parker 1, 2850–3046 m (196 m).

In the southeastern Dampier Sub-basin at Rosemary 1 and Lewis 1A, the formation grades into shale which is better assigned to the Gearle Siltstone. The problems of precise lithological correlation are typified in the section in Lewis 1A, where the age equivalent of the Haycock Marl is developed between 1295 m and approximately 1535 m. This unit overlies shale of (approximately) Aptian age which is correlated with the Windalia Radiolarite, but the boundary between the two is uncertain. The Gearle Siltstone in this well is overlain disconformably by the Campanian Withnell Formation because, in this area, the Toolonga Calcilutite has been removed by erosion.

In the southern part of the sub-basin, the Haycock Marl and the Gearle Siltstone apparently inter-tongue. In Wilcox 1, the Haycock Marl extends from 2873 m to 3130 m. Within it is an interval of claystone and glauconitic siltstone (between 2931 and approximately 3020 m) which is correlated with the Gearle Siltstone.

Fossils and age

The age of the base of the lower unit may lie somewhere within the early Albian, but the planktonic foraminiferal faunas (of *Hedbergella infracretacea*, *H. planispira*, *Globigerinelloides* sp.) are too long-ranging to give a precise age. Higher in this unit, the appearance of species such as *Ticinella roberti* and *Rotalipora ticinensis* is indicative of a definite Albian age. These species are succeeded by *Planomalina buxtorfi*, marking the Albian-Cenomanian boundary, and various species of *Rotalipora* which subdivide the Cenomanian.

The clay marker horizon lies immediately above the extinction horizon of *Rotalipora* spp., and marks the Cenomanian/Turonian boundary.

The lower part of the Haycock Marl is thus a time equivalent to the Gearle Siltstone, which is dated as Albian-Turonian by Belford (1958) and Quilty (in Playford and others, 1975, p. 297).

The upper unit spans the Turonian, Coniacian and earliest part of the Santonian, as indicated by the presence of planktonic foraminifers which include (sequentially) *Globotruncana helvetica*, *Praeglobotruncana* spp., *Clavihedbergella simplex* and the highest occurrences of *Hedbergella amabilis* and *Globotruncana renzi*.

Environment of deposition

The planktonic-dominated foraminiferal assemblages of the lower marly unit of the Haycock Marl indicate that it was deposited in open-marine conditions. In the lower part of this unit the assemblages contain up to 90% *Hedbergella*, with low numbers of benthonic species, suggesting an outer-shelf environment. The influx of *Rotalipora* species indicates that the environment deepened from outer-shelf to shelf-edge by the Late Cenomanian.

The Cenomanian/Turonian boundary is marked by the claystone horizon. This widespread unit is generally devoid of calcareous foraminifers yet contains pyritized radiolarians and arenaceous foraminifers. This claystone bed is preceded by a benthonic-rich assemblage dominated by perforate calcareous species in the type section, and in Walcott 1, Parker 1 and Haycock 1. Apthorpe (1979) postulated a shoaling of the calcite compensation depth, which would have selectively dissolved the calcareous foraminifers and left an arenaceous foraminiferal residue and a siliceous radiolarian component. An alternative explanation, involving a global oxygen-minimum event, places this event in perspective with other Cenomanian/Turonian boundary phenomena. This stage boundary is often marked in well-studied sections around the world by bituminous rich shales which correspond to a peak in C^{13} and weight percentage of organic carbon (Scholle and Arthur, 1980). An oxygen-minimum event on a global scale was suggested by Scholle and Arthur, and other workers, to account for these geochemical features and for the extinction of the planktonic rotaliporids. We suggest that the oxygen-depleted waters were accompanied by low pH, leading to the solution of any calcareous material and the pyritization of the radiolarians.

Sedimentation continued throughout the Turonian and Coniacian with planktonic-dominated assemblages. The abundance of *Globotruncana* species in this interval is indicative of deposition in slope to shelf-edge water depths.

Glauconitic sandstone intervals in the upper unit appear to be restricted to the Haycock 1/Fisher 1 area. The abundance of planktonic foraminifers within them, the current-alignment of the foraminifers, and the deep-water deposits bounding the bodies, suggest that they are grain flows or turbidites.

GEARLE SILTSTONE

Definition

The Gearle Siltstone was named by Condon (1954) and defined by Condon and others (1956). It is a silty and clayey sequence, with appreciable radiolarian siltstone, which conformably overlies the Windalia Radiolarite and is unconformably overlain by the Toolonga Calcilutite. The Gearle Siltstone grades laterally into the Alinga Formation in the southern Carnarvon Basin, and the Haycock Marl in the Dampier Sub-basin. The type section, in C-Y Creek in the Giralia Anticline, does not extend down to the base of the formation. Complete sections are possible in the Remarkable Hill area, but are still poorly exposed.

Lithology

The Gearle Siltstone is poorly exposed except in dams, and most "outcrop" consists of weathered soil immediately overlying the formation. The dominant lithotype is argillaceous siltstone, grading to silty claystone. In dams, it is dark grey to black, with a sulphurous odour. Greenish and brownish tints result from glauconite and carbonaceous material, respectively. The siltstone is commonly pyritic and glauconitic and, if clay content is low, micaceous. The clay is bentonitic.

In the Giralia Anticline, radiolarian siltstones occur near the top and base of the Gearle Siltstone. On superficial examination, these appear identical to the Windalia Radiolarite and are distinct from it only because of their stratigraphic position. Primary, bedded barite and gypsum are present in outcrop; botryoidal barite nodules, with a central crystalline gypsum core, occur near the top of the formation. These nodules also commonly contain marcasite. A possible tuffaceous sandstone is present on the eastern side of the anticline near Black Dam (Harrison, 1979).

In the subsurface the Gearle Siltstone is similar to the underlying Windalia Radiolarite and the contact is commonly picked from electric logs and palynology. The formation is generally slightly to very calcareous, reflecting low terrigenous supply. This calcareous component is commonly in the form of concretions or thin lenses of limestone, only rarely dolomitized. In the Barrow Sub-basin, WAPET recognize unnamed upper and lower members. The upper member is calcareous and glauconitic, but they are otherwise similar.

Distribution and thickness

The Gearle Siltstone is readily distinguished from the Windalia Radiolarite and Toolonga Calcilutite in outcrop except in the transitional boundary zones. The formation extends through most of the Carnarvon Basin. It grades into a more restricted (environmentally), thinner lateral correlative, the Alinga Formation in the Shark Bay area, and into a deeper water equivalent, the Haycock Marl, in the Dampier Sub-basin. Similar sediments have been recognized as far northwest as the Exmouth Plateau.

The unit does not thin markedly to the west as do the underlying formations. The greatest penetrated thickness of the Gearle is over 700 m, in the Spar 1–Tryal Rocks 1 area. Though the sediments do thin westwards, over 350 m of Gearle Siltstone occurs on the Rankin Platform in West Tryal Rocks 2. Towards the eastern basin margin the formation gradually thins and, at the end of the Turonian, a period of non-deposition occurred, further reducing the total thickness. In outcrop the unit is 120–170 m thick in the Giralia Range and about 90 m west of Kennedy Range (Condon, 1968). It thins further in the south near the Wooramel River.

In the Giralia Anticline, drilling indicated that local variations in thickness were due to the presence of a number of small local basins, in which greater than average thicknesses of Gearle Siltstone accumulated.

Environment of deposition

The Gearle Siltstone is a low-energy, offshore-marine deposit. Terrigenous input was low, and sea-floor conditions were restricted, although there is no indication that the basin was barred. Onshore areas were in an inner-shelf setting, while northern parts of the basin ranged from middle-shelf to outer-shelf conditions and, by the end of the Turonian, shelf-edge and slope conditions (Apthorpe, 1979).

The presence of a possible tuffaceous sandstone in the Giralia Anticline (Harrison, 1979, 1985) suggests submarine volcanism, from an unknown source nearby. Volcanism would provide a source for the bentonitic clays and the radiolarian blooms. It should be noted that the identification was based on one thin bed and is not unequivocal.

Fossils and age

The Gearle Siltstone contains a varied foraminiferal assemblage, particularly in calcareous facies, which has enabled precise determinations of age and palaeoenvironment. Other macrofossils include belemnites and bivalves. Belemnite guards are the most common fossils in outcrop.

The Gearle Siltstone is Albian to Turonian in age (Belford, 1958; Belford and Scheibnerova, 1972).

ALINGA FORMATION

Definition

The Alinga Formation ("Alinga Beds" of Clarke and Teichert, 1948; "Alinga Greensand" of Fairbridge, 1953; amended by Johnstone and others, 1958) is a glauconitic claystone and siltstone sequence, which outcrops in the lower Murchison River area and grades laterally into the Gearle Siltstone in the Shark Bay area. It rests

conformably on Windalia Radiolarite and is disconformably overlain by Toolonga Calcilutite. The 15 m thick type section is at Alinga Point, near Kalbarri. Another well-exposed section is at Stone Wall, on Murchison House Station.

Lithology

The Alinga Formation is a monotonous sequence of dark-green glauconitic clayey siltstone and silty claystone, with lesser greensand. Glauconite is a constant accessory. In some localities it is highly carbonaceous and black in colour. Pyrite nodules are also present, though not abundant. The siltstone locally coarsens and is winnowed, to form small lenses of fine, argillaceous, glauconitic sandstone. Bedding is poorly developed and blocky in most outcrops.

The Allinga Formation is difficult to distinguish from the Windalia Radiolarite in very fresh exposures.

Distribution and thickness

The Alinga Formation outcrops on Murchison House Station near the Lower Murchison River and in isolated exposures near Modesty Villa and Gie Gie outcamps. It is an aquiclude, and the Toolonga Calcilutite commonly slips over it to rest on the Windalia Radiolarite, resulting in very poor outcrop. It has been identified in water bores as far north as Shark Bay, where it presumably is transitional into the Gearle Siltstone. The formation is generally only 10 to 20 m thick.

Environment of deposition

The Alinga Formation formed in a shallow-marine environment with restricted circulation, relatively close to shore on outcrop areas. Energy levels were generally low, with higher energy interludes which winnowed the glauconite and sand to form local greensands and sandstones. This suggests deposition mostly occurred below wave base.

Fossils and age

Radiolarians, foraminifers, belemnites, and microscopic fish teeth have been recovered from the Alinga Formation but are not abundant and have not been studied. The stratigraphic position of the unit suggests that, like the Gearle Siltstone, it is Albian to Turonian in age.

UNGROUPED UNITS

TOOLONGA CALCILUTITE

Definition

Clarke and Teichert (1948) erected the "Toolonga Chalk" for a chalky calcilutite sequence in the lower Murchison River area. Later mapping showed that the overlying formation, the Second Gully Shale (also erected by Clarke and Teichert) could not be consistently distinguished from the Toolonga Chalk. As both formations were fine-grained carbonates, Johnstone and others (1958) amended the name to Toolonga Calcilutite, and extended the definition to include the Second Gully Shale. The type section is 2 km north of Yalthoo Bore on Murchison House Station. The interval between 2602 and 2642 m in Goodwyn 6 (Fig. 100) provides a reference section in the northern Carnarvon Basin.

The Toolonga Calcilutite is disconformable on older sediments, except in the Dampier Sub-basin where it is conformable on the Haycock Marl. In some areas it grades laterally into, and is conformably overlain by, the Korojon Calcarenite or (in the Dampier Sub-basin) the Withnell Formation. Elsewhere, it is conformably overlain by the Miria Marl.

Lithology

In outcrop, the Toolonga Calcilutite is a generally massive, fossiliferous calcilutite and calcisiltite, which weathers white, pale green or pale grey. Some glauconite is usually present. Small fragments of *Inoceramus* are very common. Phosphatic nodules are locally present at the base and top of the unit, indicating very slow deposition. In some outcrops, superficial quartz sand has been incorporated into weathered Toolonga Calcilutite which has subsequently been relithified. This gives the false impression that the rock is quite sandy.

There is little variation in the Toolonga Calcilutite in the subsurface. It is slightly coarser grained over topographic highs and near basin margins. In Pepper 1 and Onslow 1, for example, the formation consists largely of terrigenous silt, reflecting both shallow conditions and the proximity of basement. Pyrite and glauconite are generally present in trace amounts. Heath and Apthorpe (written comm.) state:

"In the Dampier Sub-basin, the calcilutite is white to greenish white to bluish white, and is composed predominantly of planktonic foraminifera, which are not grain supporting, and nannofossils. *Inoceramus* prisms are rare to absent. The formation contains up to 5% calcite silt, up to 10% clay minerals and traces of pyrite in places.

"The limits to the formation are most apparent using the compensated neutron porosity/formation density (limestone calibrated), gamma-ray and sonic well logs.

"The lithologic contrast at the top of the formation, with the overlying Withnell Formation, is correlated with the seismic D horizon of Woodside (Apthorpe, 1979)".

Distribution and thickness

The Toolonga Calcilutite forms outcrops in the lower Murchison River area, around Hamelin Pool, on the west side of Kennedy Range, and in several coastal anticlines. It is near the surface throughout the Gascoyne Sub-basin, extends through all the Mesozoic sub-basins on to the Exmouth Plateau and to the Beagle Sub-basin of the Canning Basin.

Onshore, the Toolonga Calcilutite is generally between 50 and 100 m thick, thickening overall to the west and north, but also locally, as in Peron 1 where the unit may be about 270 m thick. The formation grades laterally into the Korojon Calcarenite in the Giralia Anticline. Offshore, the unit reaches to a maximum of more than 600 m in the Trimouille 1 area, and thins to between 60 and 80 m over the Rankin Platform.

In the Dampier Sub-basin, the Toolonga Calcilutite ranges from 30 m (Lambert 1) to 99 m thick (Withnell 1). Seismic evidence suggests that in some inshore areas of the sub-basin the Toolonga Calcilutite has been removed by pre-Campanian erosion on structural highs (Heath and Apthorpe, written comm.).

Fossils and age

The formation is rich in foraminifers, locally meriting the term "foraminiferal limestone" (Apthorpe, 1979), and this has allowed precise age dating. In the southern Carnarvon Basin, the Toolonga Calcilutite is Santonian to Campanian in age (Belford, 1958). In the northern onshore Carnarvon Basin, it locally ranges upwards into the Maastrichtian (McWhae and others, 1958; Cockbain, written comm.). Belford (1983) described Coniacian foraminifers from probable Toolonga Calcilutite in the Giralia Anticline, indicating that deposition probably commenced earlier in the northern than in the southern Carnarvon Basin. In the Dampier Sub-basin, the presence of *Globotruncana concavata carinata* throughout the formation and *Globotruncana renzi* near the base of the unit indicate a Santonian age (Heath and Apthorpe, written comm.).

In addition to foraminifers and the bivalve *Inoceramus*, the Toolonga Calcilutite contains ostracods (Bate, 1972), bryozoans, pelagic crinoids, serpulids and sponges (Rigby, 1983). Bivalves, including small oyster-like forms, and brachiopods are common in shallower water facies. Abundant *Inoceramus* fragments commonly "mask" other fossils.

Environment of deposition

The Toolonga Calcilutite is a calcareous pelagic deposit. Heath and Apthorpe (written comm.) state: "The proportion of planktonic species in the foraminiferal assemblages is in excess of 90%, indicating an outer shelf to slope environment from the Rankin Platform to Brigadier 1 and Delambre 1 (Apthorpe, 1979). Limited data quoted by Clark (1979) suggest that the planktonic percentage of the Toolonga Calcilutite ranges between 15% and 75% in the onshore Carnarvon Basin. This lower abundance suggests that the offshore areas around the Rankin Platform are significantly deeper than the onshore Carnarvon Basin." Elsewhere in the Carnarvon Basin, inner to middle shelf conditions prevailed. Energy levels were low except for isolated areas such as the Giralia Anticline, which was structurally and topographically high. Near the basin margin there was some dilution of the carbonate by terrigenous detritus.

The generally low volume of terrigenous material in the formation was attributed by Apthorpe (1979) to a dry climate and low continental runoff. The calcareous bloom occurred probably as a result of globally changed oceanic circulation patterns, after the breakup of Gondwana, which introduced warmer waters to the northwestern Australia.

WITHNELL FORMATION

(R.S. Heath and M.C. Apthorpe)

Definition

The Withnell Formation (Heath and Apthorpe, 1984) is a fine-grained siliciclastic correlative in the Dampier Sub-basin of the upper

part of the Toolonga Calcilutite and the Korojon Calcarenite. The type section is in Goodwyn 6 between 2469 and 2602 m (see Fig. 100). The formation conformably overlies the Toolonga Calcilutite and is disconformably overlain by the Miria Formation.

Lithology

The Withnell Formation consists of olive-black to olive-grey claystone and calcareous claystone, with traces of micrite, pyrite, glauconite, common *Inoceramus* prisms, and foraminifers. Northwards from the Goodwyn area, the unit grades into soft marls. Within the formation, thin beds of light-grey marl have a higher *Inoceramus* and foraminiferal content than the remainder of the formation.

The basal 10 to 25 m interval, immediately above the Toolonga Calcilutite, is typically a soft calcareous claystone-marl of early Campanian age and is distinguished from the underlying calcilutite and overlying claystone by its slower sonic-log response (Fig. 100).

The top of the formation is distinguished from the overlying Miria Formation by the higher clay content of the Withnell Formation. The disconformable boundary is normally visible as a reduction in the gamma-ray log response.

Distribution and thickness

The Withnell Formation extends across the North West Shelf from Lewis 1A westwards to Brigadier 1, and from Withnell 1 in the south to Delambre 1 in the north. Its thickness varies markedly, from 66 m in Delambre 1 (2102–2168 m) to approximately 514 m in Withnell 1 (1520–approx. 2034 m).

Fossils and age

Planktonic foraminifers indicate the formation ranges in age from Early Campanian to Early Maastrichtian (Fig. 100). The successive last appearance horizons of *Globotruncana marginata* plus *Globotruncana elevata*, *Globotruncana ventricosa* and *Globotruncana lapparenti* are used for biostratigraphic correlation of this time interval over the North West Shelf. Evidence for the Maastrichtian age of the top of the formation is provided by the occurrence of *Bolivinoides draco draco* in Brigadier 1 at 2643 m.

Environment of deposition

An abrupt change in foraminiferal biofacies (and therefore palaeoenvironment) corresponds to the change from the carbonate-rich Toolonga Calcilutite to the fine-grained clastic sediment of the Withnell Formation. A rapid decline in numbers of foraminiferal specimens and the increasing relative abundance of *Rugoglobigerina* and *Heterohelix* at the expense of *Globotruncana* indicates shoaling from the outer-shelf conditions of the Toolonga Calcilutite. The relative proportion of planktonic to benthonic foraminifers (and in particular the arenaceous benthonic component) suggests that the environment of deposition fluctuated from middle to inner shelf during the Campanian to early Maastrichtian. Four abundance peaks of arenaceous benthonic foraminifers, probably coinciding with inner-shelf conditions, are present in Parker 1, Withnell 1 and Walcott 1. It is possible that these arenaceous foraminiferal peaks represent synchronous fluctuations in sea level across the Dampier Sub-basin. Further south in the onshore Carnarvon Basin, a continuation of the carbonate regime resulted in deposition of the upper part of the Toolonga Calcilutite, and the succeeding Korojon Calcarenite (Belford, 1960; Clark, 1979). The facies relationships of these carbonate formations with the clastic Withnell Formation require further study.

KOROJON CALCARENITE

Definition

The Korojon Calcarenite was named by Condon (1954) and defined by Condon and others (1956). It is a coarser grained facies correlative of the upper Toolonga Calcilutite. It conformably overlies and is gradational from the Toolonga Calcilutite, and is disconformably overlain by the Miria Formation. The type section is in C-Y Creek in the Giralia Anticline. The thickness of the section as defined by Condon (1968) is 38 m, but this includes about 15 to 20 m of Toolonga Calcilutite which he did not recognize.

Lithology

The Korojon Calcarenite consists of pale coloured, silty calcarenite and calcisiltite with abundant large fragments of the bivalve *Inoceramus*. The matrix is a mixture of lime mud, microfossils, fossil fragments, and numerous prisms of calcite (originally aragonite) formed by the disaggregation of *Inoceramus*, which together form a coarse bioclastic packstone. Small glauconite pellets, pyrite crystals and aggregates

and phosphatic-nodule horizons are also present. In a few localities, thin greensand interbeds are present near the top of the formation, together with phosphate-nodule horizons. Scattered quartz sand grains occur and locally form a calcareous sandstone.

Distribution and thickness

The formation forms extensive low scarps with relatively good exposures around the Giralia and Marrilla Anticlines, and has been tentatively recognized in some other anticlines north of the Gascoyne River. The maximum thickness is at the northern end of the Giralia Anticline where the combined thickness of it and the Toolonga Calcilutite is about 45 m. This thins to a combined thickness of less than 25 m at the southern end of the anticline. Identifications of Korojon Calcarenite in water bores, petroleum-exploration wells (*e.g.* Centenary Bore, Cardabia; Brickhouse 4; Rough Range 1; Hilda 1A) are largely inaccurate. From the descriptions, only small thicknesses of Korojon Calcarenite are present, and most of each intersection is better assigned to the Toolonga Calcilutite.

Environment of deposition

The Korojon Calcarenite is a moderate-energy, partially winnowed equivalent of the Toolonga Calcilutite which formed in shallower water depths. Condon (1968) suggested that the abundant *Inoceramus* shells were shoal banks, built up by very rapid growth of the animals under exceedingly favourable conditions, but shoaling action is unlikely. Any mechanical concentration of the shells would have fragmented them far more than they are. The unit is essentially an *in situ* accumulation of shells in a lime-mud and silt environment with high biogenic activity.

Fossils and age

As well as the ubiquitous *Inoceramus* shells, the Korojon Calcarenite contains foraminifers (Edgell, 1957; Belford, 1958, 1960), ostracods (Bate, 1972), and ammonites (Brunnschweiler, 1966). The foraminifers indicate a Campanian to early Maastrichtrian age, although the fact that the underlying Toolonga Calcilutite extends into the Maastrichtian in the Giralia Anticline (Cockbain, written comm.) suggests that the Korojon Calcarenite is mostly Maastrichtian rather than Campanian.

MIRIA FORMATION

Definition

The Miria Formation was named by Condon (1954) as Miria Marl, and defined by Condon and others (1956). Henderson and McNamara (1985a) modified the name. It disconformably overlies the Korojon Calcarenite, Toolonga Calcilutite or Withnell Formation, and is unconformably overlain by the Cardabia Calcarenite, Lambert Formation or Dockrell Formations. The latter relationship applies in areas of the Dampier Sub-basin which were structurally too high to be inundated during the Early Paleocene. The type section is in Toothawarra Creek on the western limb of the Giralia Anticline and is 1.2 m thick. A reference section for the Miria Formation in the Dampier Sub-basin is in Goodwyn 6 between 2437.5 and 2469 m (Fig. 100).

Lithology

In outcrop, the Miria Formation consists of two lithotypes, a pale fine-grained calcarenite and a white to pale greenish-grey calcisiltite with a marly appearance, after which the formation was originally named. The calcarenite is absent in offshore areas, and clay is more abundant, resulting in a common gradation from marl to calcareous claystone. Glauconite is common, giving a greenish colouration. In the Giralia Anticline, the base of the unit is usually marked by a layer of phosphatic nodules and phosphatized macrofossils. Henderson and McNamara (1985a) placed this layer (which contains *Inoceramus* fragments) in the Korojon Calcarenite, because the Miria Formation lacks *Inoceramus*. The upper contact is marked by the change from whitish marl to greensand, and siderite-cement nodules locally occur near the top of the marl in the subsurface. In outcrop, the formation contains phosphate nodules and abundant phosphate moulds (Henderson and McNamara, 1985b).

In the Dampier Sub-basin, "The main lithological difference between the Miria and adjacent formations is its higher carbonate content, usually expressed as a pale-coloured marl. In sequences such as Goodwyn 6 (Fig. 100), where three fine-grained, variably calcareous formations are contiguous, the wireline-log character changes are subtle at formation boundaries. In other wells (for example, Lambert 1; Fig. 101), the lithological and wireline-log contrast at the top of the Miria Formation is distinct." (Heath and Apthorpe, written comm.).

Distribution and thickness

The Miria Formation outcrops in the Giralia and Marrilla Anticlines. Although Playford and others (1975) stated that it was present in more southerly anticlines, it was not recognized in the present study (Denman and van de Graaff, 1982; Hocking, Williams, Lavaring and Moore, 1985). The thickness in outcrop ranges from 0.6 to 2.1 m.

In the Mesozoic sub-basins, the formation is much thicker and extends through the Dampier and Barrow Sub-basins to as far offshore as the Exmouth Plateau. The greatest thicknesses are, understandably, in the centres of the sub-basins. Heath and Apthorpe (written comm.) note that, in the Dampier Sub-basin: "It is recognizable throughout the area bounded by Delambre 1, Withnell 1, Lewis 1A and the Rankin Platform. The formation is significantly thicker on the North-West Shelf than in outcrop, with 31.5 m in Goodwyn 6, 34 m in Delambre 1 and a maximum known thickness of 70 m in Withnell 1. The age equivalent of the Miria Formation in Rosemary North 1 consists of 72 metres of calcareous, sporadically sandy claystone. In a few wells (*e.g.* Dockrell 1) the Miria Formation has been eroded during the earliest Tertiary, and the Palaeocene Dockrell Formation directly overlies the Withnell Formation."

Environment of deposition

Deposition of the Miria Formation began in the wake of a late Maastrichtian transgression (Apthorpe, 1979) which resulted in very quiet, shelf conditions over the northern Carnarvon Basin. Middle- and inner-shelf environments prevailed in the Barrow and northern Gascoyne Sub-basins. In the Dampier Sub-basin, Heath and Apthorpe state: "The abundant and diverse planktonic foraminifera present in the Miria Formation from Lewis 1A to Brigadier 1 indicate deposition in an outer-shelf environment. Similar faunas are present in wells in the Legendre area in the eastern part of the Dampier Sub-basin area. Rosemary North 1 contains a probable middle-shelf foraminiferal assemblage, dominated by benthonic species. The Miria Formation appears to be absent in Enderby 1." The presence of phosphate nodules and phosphatized fossils suggests that the unit is a condensed sequence, while the generally fragmentary nature of the fossil fauna suggests periods of higher hydrodynamic activity which winnowed the sequence (Henderson and McNamara, 1985b).

Fossils and age

The Miria Formation is very fossiliferous, and contains foraminifers, ammonites, nautiloids, brachiopods, bryozoans, gastropods, bivalves, corals, fish teeth, and radiolarians. Brunnschweiler (1966) considered that the unit was late Campanian to early Maastrichtian, based on heteromorph ammonites, although Henderson and McNamara (1985a) believed that the non-heteromorph ammonites to be entirely Maastrichtian. The foraminifers (in particular the presence of *Abathomphalus mayaroensis*) indicate a late Maastrichtian age (Edgell, 1957; Belford, 1958; McGowran, 1968; 1977, p. 424; Wright and Apthorpe, 1976; Apthorpe, 1979).

CHAPTER 10

Cainozoic

Cainozoic sedimentation in the Carnarvon Basin has taken place primarily in the northern, largely offshore, part of the basin, and has been dominated by carbonate deposition. Most of the onshore portion of the basin was subject to erosion and duricrusting throughout the Cainozoic, except for two periods of siliciclastic deposition in the Eocene and Miocene, when the Merlinleigh Sandstone and Pindilya Formation were deposited.

The most complete sequence of Cainozoic sediments is in the Dampier Sub-basin and Rankin Platform area. There, the onshore stratigraphy is difficult to apply, and for this reason Heath and Apthorpe (1984) proposed several new stratigraphic units. This is the only substantial modification to the earlier stratigraphy.

Quilty (1977, 1980) recognized several sedimentation cycles in the Exmouth, Barrow and northwestern Gascoyne Sub-basins, where they constitute obvious, unconformity-bounded divisons of the Cainozoic sequence. The cycles can also be discerned in the Dampier Sub-basin. They are commonly separated by a period of non-deposition, rather than erosion, and are as follows:

(a) Paleocene to Early Eocene (Cardabia Calcarenite, Dockrell Formation, Wilcox Formation, Lambert Formation).

(b) Middle to Late Eocene (Giralia Calcarenite, Walcott Formation).

(c) Late Oligocene to Middle Miocene (Cape Range Group).

(d) Late Miocene to Holocene (Delambre Formation).

Identification and correlation of Tertiary units in most of the onshore part of the Basin are hampered by extensive Pliocene-Pleistocene eolian deposits and (in most cases) by the lack of fossils.

The age of some Tertiary units is discussed in terms of a "T" zonation, where the international P-zonation cannot be applied easily. The "T" zonation is an (at present) informal zonation developed by Woodside for the North West Shelf.

Coastal Quaternary units of the Carnarvon Basin have been named in the Cape Range and Shark Bay areas.

In the Cape Range area, Condon and others (1953) and Condon (1954) established the Exmouth Sandstone, Mowbowra Conglomerate and Bundera Calcarenite. Van de Graaff and others (1976) defined the Milyering and Muiron Members of the Exmouth Sandstone, and the Jurabi and Tantabiddi Members of the Bundera Calcarenite. Van de Graaff and others (1980) reduced the Mowbowra Conglomerate to member status within the Bundera Calcarenite. The Exmouth Sandstone and Bundera Calcarenite were extended south to the Lake MacLeod area by Denman and van de Graaff (1977, 1982) and Hocking, Williams, Lavaring and Moore (1985), and northeast to Onslow and Long Island by van de Graaff and others (1982).

In the Shark Bay area, the Peron Sandstone, Tamala Limestone, Dampier Limestone (including the Carbla Oolite Member), Bibra Limestone, Depuch Formation and Hamelin Coquina were initially defined by Logan (1968) and Logan, Read and Davies (1970). Van de Graaff and others (1983), and Playford and others (1976) subsequently modified some names. Of these units, the Bibra Limestone has been extended north almost to Carnarvon along the eastern shoreline of Shark Bay.

The marine-dominated Pleistocene sediments were thought to have been deposited during the last two interglacials, and therefore were divided into two units, the Dampier and Bibra Limestones. However, electron-spin resonance dating of shells from several localities of Dampier Limestone suggests that the unit spans more than one interglacial (Hewgill and others, 1983), parts of it being considerably older than previously thought. This casts some doubts on the validity of the Dampier Formation and the Carbla Oolite Member, as extended around Shark Bay; but insufficient detail is known yet to resolve the question.

3135—12

LAMBERT FORMATION

(R. S. Heath and M. C. Apthorpe)

Definition

The Lambert Formation (Heath and Apthorpe, 1984) is an Early Palaeocene sequence in the Dampier Sub-basin which has no time equivalent elsewhere in the Carnarvon Basin. It disconformably overlies the late Maastrichtian Miria Formation. In different areas, it is conformably or disconformably overlain by the Late Paleocene Dockrell Formation. The Lambert Formation consists of claystone, commonly with an upper member of silty sandstone. Marked, lateral, facies variations occur over very short distances, because of deposition on an irregular topography. The type section is in Lambert 1 between 2449 and 2502 m, but does not contain the sandy upper member. The interval between 2515 and 2580 m in Miller 1 is proposed as a reference section for this facies (Fig. 101).

Lithology

The type section of the Lambert Formation consists entirely of moderately hard, slightly silty claystone, mostly olive black in colour, but varying from dark greenish grey to dark grey, and containing up to 10% micrite, up to 5% foraminifers, and a trace to 5% glauconite.

In Miller 1, the sandy upper member is a light-grey to olive-grey, very fine-grained, moderately well-sorted sandstone with 5–15% glauconite, less than 10% micrite and clay minerals, and poor intergranular porosity (Fig. 101). This grades up into a sandy siltstone, variably clayey and slightly glauconitic. The distinction between fine sandstone and siltstone in other wells appears to have been a matter of individual judgement.

Several other sections illustrate the lithological variation of the Lambert formation. In North Rankin 6 the formation occurs between 2578 and 2660 m, of which the top 60 m is the upper sandy facies.

In Dampier 1, the Lambert Formation occurs between 1298 and 1546 m. Claystone is transitional upwards into sandstone between 1463 and 1513 m, and the top of the sandy, upper facies is at the top of a massive sandstone sequence. The overlying Dockrell Formation is atypically sandy, but more calcareous than the Lambert Formation, with lesser lithological differences than in most wells.

In Lewis 1A the Lambert Formation is claystone throughout, between approximately 800 and 1095 m. Foraminifers indicate the presence of zones T2 and T1, *i.e.* that the upper part of the claystone is the time equivalent of the sandy member developed in some other wells.

In Withnell 1 the Lambert Formation is an interbedded sequence of siltstone, fine sandstone and claystone. The top of the formation is placed, somewhat arbitrarily, at a siltstone bed at 1210 m, as the lithological interpretation is complicated by caving from the overlying Dockrell Formation. The base of the formation lies at 1435 m.

Distribution and thickness

The Lambert Formation has a widespread distribution north and west of the Rankin Platform, extending as far as Delambre 1 and Brigadier 1. Around the Rankin Platform and east as far as Lewis 1A, the formation has a distribution pattern suggesting deposition on an irregular topography, presumably developed in the earliest Tertiary. In this area, two shallow-marine embayments probably existed: one extending southwest along the inner edge of the Rankin Platform from Miller 1 to Wilcox 1, and one oriented southeast from Lambert 1 to Lewis 1A. The formation is 53 m thick in the type section, and 75 m thick in the main reference section.

Fossils and age

The Lambert Formation is Early Paleocene in age. The lower part of the unit contains the planktonic foraminifers *Globoconusa daubjergensis*, *Planorotalites compressa*, *Subbotina pseudobulloides* and *Subbotina triloculinoides* indicating a zone T1 age. This assemblage suggests a correlation with the Early Paleocene planktonic zones Pld-P2 (Heath and Apthorpe 1981). The upper part of the unit lacks *Globoconusa daubjergensis* and contains *Morozovella uncinata* in association with the other species listed. The extinction of *Morozovella uncinata* has been placed at the top of zone T2 (*i.e.* approximately within zone P3 (Heath and Apthorpe, 1981).) The planktonic foraminifers in the upper part of the Lambert Formation are lacking in diversity, and the species present are inadequate in this part of the formation to use the international "P" zones.

The presence of *Morozovella pusilla* (*sensu lato*) in the uppermost part of the glauconitic siltstone member in Miller 1 is evidence of a latest zone T2 (Early Paleocene) age. The basal part of overlying Dockrell Formation in this well is of T3

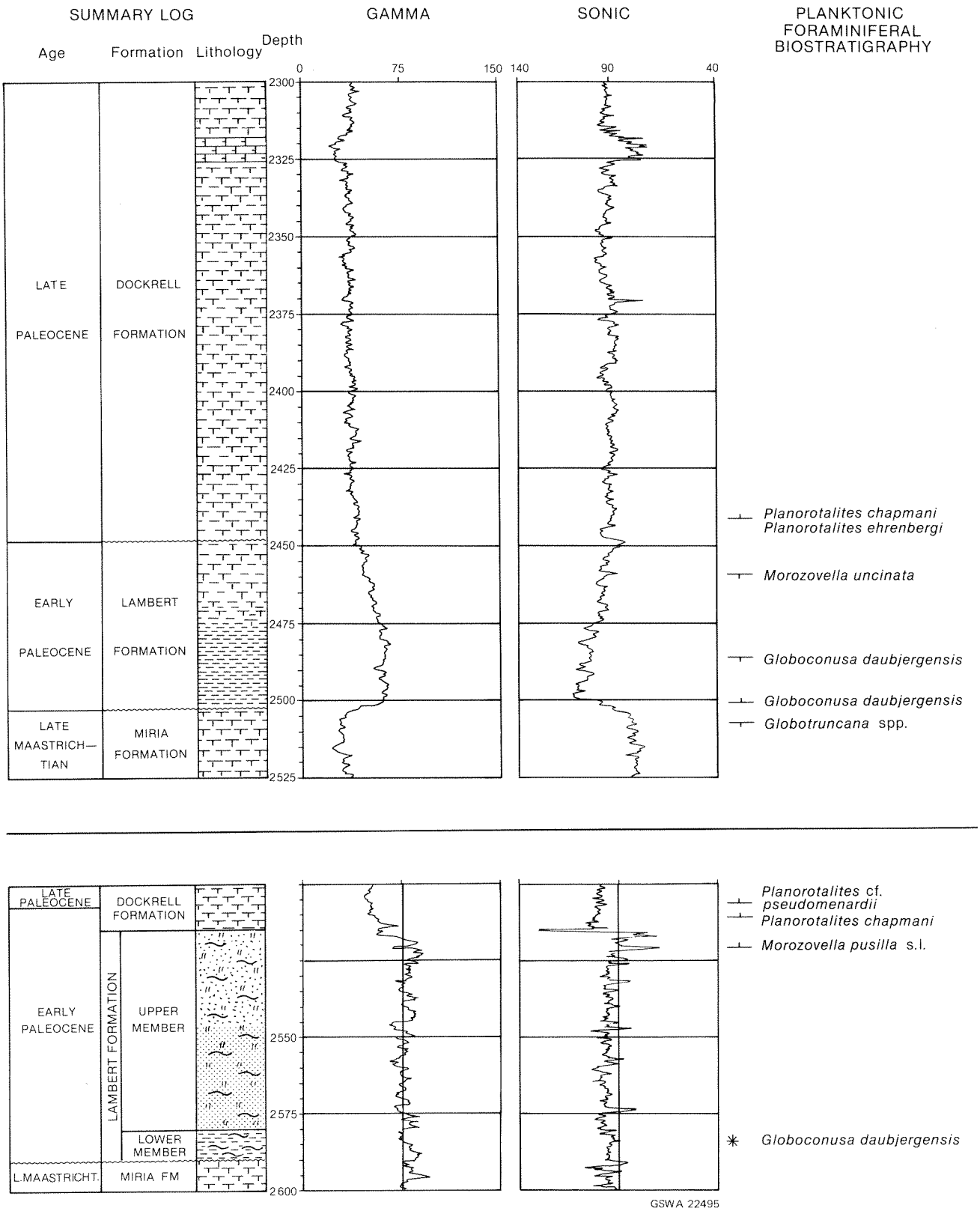

Figure 101. Type and reference sections of the Lambert Formation, in Lambert 1 (top) and Miller 1 (bottom), respectively.

age, and there appears to be no perceptible hiatus between the Lambert and Dockrell Formations in Miller 1.

Environment of deposition

The Lambert Formation was deposited during the first marine transgression of the North West Shelf in the Tertiary. Deep-water (outer shelf to ?slope) claystones occur to the north and west of the Rankin Platform while shallower, low-energy clays were deposited in embayments. Around the Rankin Platform palaeo-highs, the claystone facies passes upwards into the silts and fine sands of the upper member of the Lambert Formation.

In the embayment to the southeast of the Rankin Platform, the Lambert Formation is predominantly silty or sandy (as in Withnell 1 and Dampier 1), and foraminifers are few in number. Arenaceous benthonic genera (principally *Uvigerinammina, Haplophragmoides,* and *Ammobaculites*) are the dominant or only forms present. Both lithology and foraminifers indicate a very shallow-marine, probably shoaling, environment in this protected embayment.

CARDABIA CALCARENITE

Definition

Raggatt (1936) included all the predominantly calcareous sequence exposed in the Giralia Range between the Winning Group and the Giralia Calcarenite in the "Cardabia Series". Condon and others (1956) revised the name to "Cardabia Group", and Condon (1967) reduced the scope of the group to include only the Tertiary portion, namely the "Boongerooda Greensand" and the "Wadera", "Cashin", "Pirie" and "Jubilee Calcarenites".

The "Cardabia Group" was here reduced to formation status by Hocking (1985), and the constituent "formations" to member status, for several reasons. Firstly, the differentiation of the "formations" in the Giralia and Marrilla Anticlines depends on differences in vegetation over different units (reflecting trace-element differences) as much as lithological differences. Individual "formations" can be readily distinguished on lithological grounds only in some areas, and particular difficulty is experienced where only isolated parts of the sequence are present. This is usually the case away from the Giralia and Marrilla Anticlines. Secondly, the "Cardabia Group" is a single depositional episode, unconformity bounded in the onshore area, and of a similar magnitude to the Giralia Calcarenite or Toolonga Calcilutite. Thirdly, individual "formations" within the sequence have rarely been differentiated in petroleum-exploration wells. For these reasons the "Cardabia Group" is renamed the Cardabia Calcarenite. Named members within the formation (where they can be differentiated) are, in ascending order: the Boongerooda Greensand, Wadera, Pirie, Cashin, and Jubilee Members.

The 77 m thick type section of the Cardabia Calcarenite is in Toothawarra Creek. This contains the type sections (as designated by Condon and others, 1956) of all the members except the Jubilee Member, which is located 18 km to the north. The Dockrell Formation is a basinal equivalent of the Cardabia Calcarenite in the Dampier Sub-basin.

Lithology

In the Giralia Anticline, the Cardabia Calcarenite consists of a basal greensand (the Boongerooda Greensand Member), overlain by calcarenite and calcisiltite.

Because the formation is fully divided into members in this area, its lithology here is described in terms of those members in separate sections below.

In outcrop areas other than the Giralia Anticline, the Cardabia Calcarenite is either a yellow-greenish, hard, glauconitic calcarenite, or a chalky, locally bryozoal calcarenite and calcisiltite. It is not known whether significant, lateral, facies changes are present.

In the Cape Cuvier and Grierson Wells, the Cardabia Calcarenite is a very calcareous sandstone and calcarenite. The increased sand content compared with the Giralia Anticline presumably reflects proximity to the shoreline, with deposition near the breaker zone rather than open shelf.

Elsewhere in the subsurface, both to the north and to the south in Tamala 1, the Cardabia Calcarenite consists of claystone or calcilutite grading to calcarenite, with variable quartz sand and minor dolomite. In Tamala 1 and Hilda 1A, only the upper part of the unit was thought to be present (Kempin and Fujioka, 1973; Meath and Wright, 1974). The Boongerooda Greensand Member is locally distinguished, as in Locker 1, where it is 6 m thick (Hosemann and Parry, 1967).

Boongerooda Greensand Member: This contains between approximately 20% and 80% medium-grained glauconite sand set in a white to grey, chalky matrix. Because of generally poor exposure, the presence of the member is in most cases only indicated by a wash of greensand (with ammonite casts from the underlying Miria Formation) or green anthills. The lower contact is relatively sharp and is marked by phosphate nodules. Although a disconformity is present, there is no clear lithological evidence in outcrop. The type section, 3 m thick, is at the base of the Cardabia Calcarenite type section in Toothawarra Creek.

Wadera Member: The Boongerooda Greensand Member grades upward into the Wadera Member, which is a unit of usually hard, well-bedded, yellowish, fine- to medium-grained, glauconitic, calcarenitic grainstone to packstone, interbedded with soft marly limestone. Bryozoans are commonly abundant towards the top of the Wadera Member. Distinctive smoothly curving burrows occur throughout the unit. The bedding is on a scale of 0.5 to 1.5 m. A regular joint pattern, commonly shown in bedding-plane exposures, produces a blocky appearance in vertical section. The type section is 23 m thick and overlies the Boongerooda Greensand Member type section.

Pirie Member: This has a relatively sharp contact with the Wadera Member in the southern Giralia Anticline, but an interfingering contact in the north. The type section, 29.5 m thick, overlies the Wadera Member type section. It is a friable, chalky, white calcarenite to calcisiltite which locally is richly bryozoal. The calcarenites are wackestones to packstones, and bedding is generally poorly developed. An upper, light-coloured, hard, calcarentic unit is locally developed.

Cashin Member: The Pirie Member grades up into and interfingers with the Cashin Member, which consists of calcarenitic packstone to grainstone, showing thin to medium scale, nodular to regular bedding. It is harder than most exposures of the Pirie Member, and locally is very similar to the Wadera Member. The Cashin Member cannot be distinguished from the Pirie or Jubilee Members on a regional scale. The type section, 8.5 m thick, is in Toothawarra Creek, west of the Pirie Member type section.

Jubilee Member: This overlies the Cashin Member and, as mapped by the GSWA, is a hard, greenish, medium- to fine-grained calcarenitic packstone to ?wackestone, in places glauconitic and/or bryozoal. The type section, 10.7 m thick, is 1 km south of the Giralia-Bullara road, on the west limb of the Giralia Anticline.

Distribution and thickness

The Cardabia Calcarenite is exposed in the northwestern part of the Gascoyne Sub-basin, in the Giralia, Marrilla, Chargoo, Warroora and Gnarloo Anticlines. It may be present in the Chirrida Anticline, but was removed from the core of the Yankie Tank Anticline by pre-Miocene erosion which was associated with the early stages of formation of the coastal anticlines.

The thickness of the Cardabia Calcarenite in outcrop is difficult to measure accurately because of low dips and poor exposure. Condon and others (1956) considered that in the Giralia Anticline the unit varies from about 77 m thickness, in the area of C-Y Creek and Toothawarra Creek, to about 28 m near Korojon Pool at the southern end of the Giralia Anticline.

South of the area of outcrop, the Cardabia Calcarenite does not extend very far onshore. It is 40 m thick in Cape Cuvier 1, thinning to 30 m in Bibbawarra Bore, 22 m in Brickhouse 1, and 17 m in Grierson 1. Allen (1972a) recorded a westwards thickening wedge, more than 60 m thick, of calcareous, bentonitic claystone with minor limestone (which may be Cardabia Calcarenite) in bores, in or near the Gascoyne River between Brickhouse 1 and Carnarvon. Further south, the Cardabia Calcarenite is absent in the hills near Yaringa homestead, but is 112 m thick in Tamala 1 (Kempin and Fujioka, 1973). It is absent further south.

North of the area of outcrop, Quilty (1974) showed the general distribution, isopachs and palaeogeography of the Cardabia Calcarenite. The unit is present in the Cape Range area and north of the Long Island and Flinders Fault Systems, with an "embayment" in the Onslow 1 area (which Quilty omitted). Thickness ranges up to 75 m in Long Island 1 and more than 100 m north of Hilda 1A. It is absent in Muiron 1 and Minderoo 1.

Fossils and age

The Cardabia Calcarenite (in particular the Boongerooda Greensand Member and Wadera and Pirie Members) is richly fossiliferous and has yielded faunas consisting of planktonic and benthonic foraminifers, bryozoans, ostracods, echinoids, brachiopods, bivalves, gastropods, nautiloids, and crustaceans. Many forms are listed in Condon and others (1956), and have been de-

scribed by several authors, more recently Foster and Philip (1978), McNamara and Philip (1980) and McNamara (1983).

The macrofauna of the Boongerooda Greensand Member was studied by Brunnschweiler (1966), who assigned a Late Cretaceous age to the member. However, much of this material was reworked from the underlying Miria Formation. Foraminifers indicate a late Paleocene age (McGowran, 1968, 1978). The lowermost part of the member is late Thanetian, indicating that the disconformity between the Miria Marl and Boongerooda Greensand Member spans much of the Paleocene (McGowran, 1968).

The Wadera and Pirie Members are of Paleocene (P4) age, based on foraminiferal assemblages (McGowran, 1968), whereas the Cashin Member is Paleocene to Early Eocene (McGowran, 1968) and the Jubilee Member was dated as Middle Eocene by Brunnschweiler (1966).

Environments of deposition

The basal member of the Cardabia Calcarenite (the Boongerooda Greensand Member) is a condensed sequence which formed in quiet, uniform, shelf conditions over a long period of time. The presence of glauconite and phosphate make a water depth of less than 30 m unlikely (Bromley, 1967; Porrenga, 1967).

In the area of outcrop, the faunas from the Pirie and Wadera Members suggest deposition in an open-shelf environment. The commonly silty nature of the Pirie Member and the local abundance of fragile bryozoans indicates quieter, lower energy conditions than the cleaner Wadera Member, some of which may have accumulated as winnowed shoals. The upper Pirie Member and the Cashin and Jubilee Members probably formed in a similar open-shelf setting, as migrating shoals of calcarenite, in a generally calcilutite-calcisiltite environment. This is based on an indistinct coarsening-upward sequence seen at the approximate level of the Cashin Member, and relatively rapid variations in thickness of all three members.

During deposition of the Cardabia Calcarenite, the broad configuration of the continental margin was similar to the present-day configuration. Moving north from the outcrop area, the changes in the Cardabia Calcarenite simply reflect deepening of the depositional environment and a more distal position relative to the coastline. Quilty (1974) shows continental-shelf conditions extending from the eastern side of the Cape Range northeast to Barrow Island, and continental-slope conditions on the western side of Cape Range and northwest of Barrow Island.

DOCKRELL FORMATION

(R. S. Heath and M. C. Apthorpe)

Definition

The Dockrell Formation (Heath and Apthorpe, 1984) is a deep-water marl and claystone correlative of the Cardabia Calcarenite. The Dockrell Formation appears to conformably overlie the Lambert Formation in some wells, while in others a brief hiatus is thought to have occurred. In wells on the southern Rankin Platform the Dockrell Formation disconformably overlies the Cretaceous Miria Formation or the Withnell Formation.

The Dockrell Formation is disconformably overlain by the Late Paleocene to Early Eocene Wilcox Formation. Paleontological evidence indicates that there is a lengthy hiatus between the Dockrell and Wilcox Formations in most wells, due to submarine erosion. The type section (Fig. 102) in Dockrell 1 between 2376 and 2555 m, is the most complete Late Paleocene sequence yet found.

Lithology

The Dockrell Formation consists of olive-grey moderately soft marl and calcareous claystone, with beds of hard, pale-grey limestone developed locally. A laterally persistent argillaceous-limestone interval occurs near the base of the formation in some wells. The top of the Dockrell Formation is a disconformity surface which commonly has no lithological change, only a palaeontological hiatus. In Dampier 1, where the Dockrell Formation contains a marly, fine-sand facies, the upper boundary is a "hard ground" containing 2 cm diameter borings.

Distribution and thickness

The unit occurs over most of the North West Shelf from Delambre 1, over the Rankin Platform, to Lewis 1A. It is 179 m thick in the type section, and other sections include: Delambre 1, 1990–2062 m; North Rankin 6, 2402–2577 m; Parker 1, 2169–2425 m; Lewis 1A, 717–approximately 802 m; Goodwyn 6, 2292–2437.5 m.

Sandy equivalents of the Dockrell Formation occur in two wells, Rosemary North 1 and Dampier 1, on the southeastern edge of the Dampier Sub-basin. Such atypical sandy units are tentatively correlated with the Boongerooda Greensand Member. The Dampier 1 Paleocene sequence spans a longer time interval than that

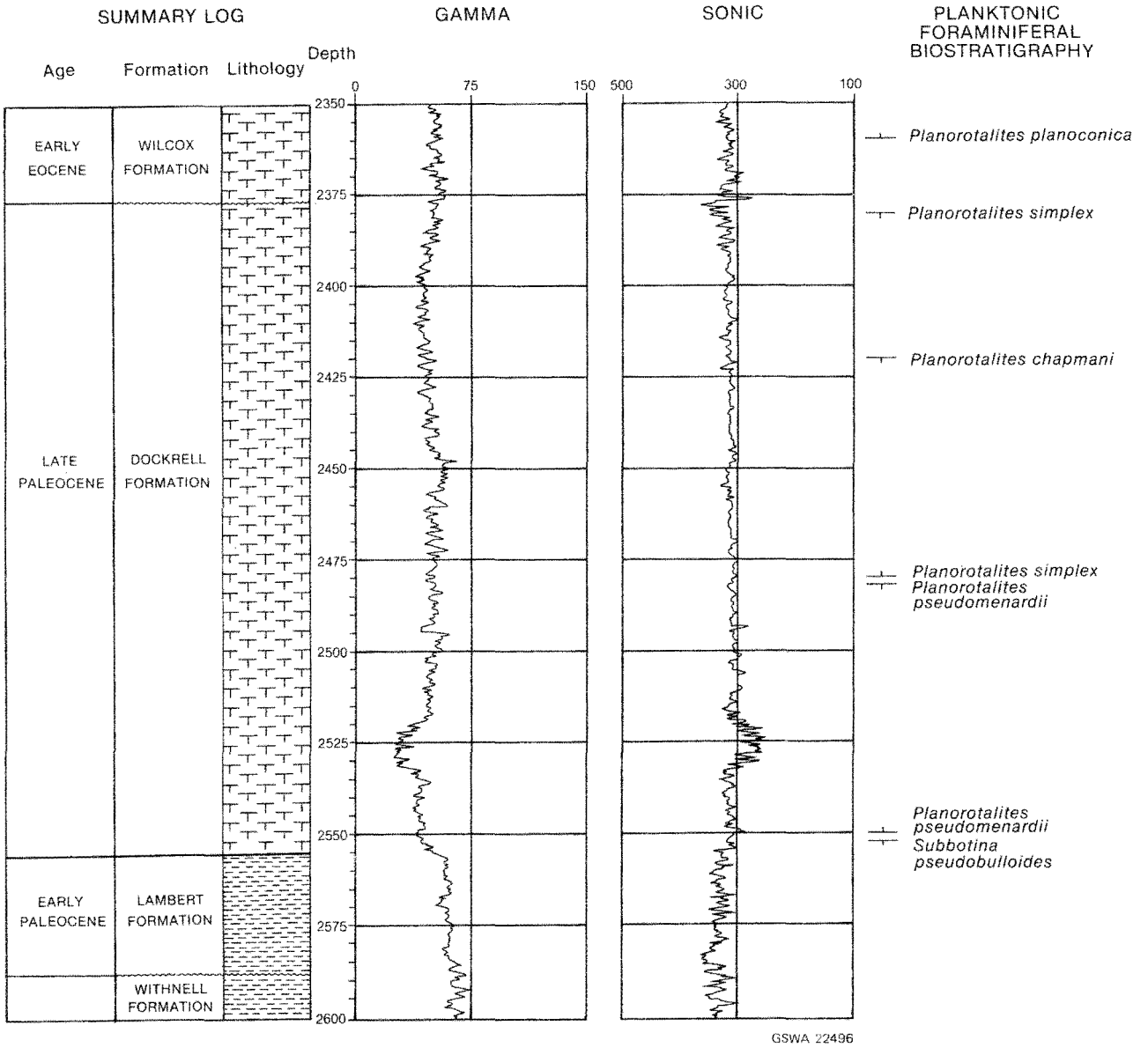

Figure 102. Dockrell Formation type section, Dockrell 1.

encompassed by the extremely thin Boongerooda Greensand, and the facies relationships require further study.

Fossils and age

The basal part of the formation in Goodwyn 6 contains *Morozovella pusilla* without *Planorotalites pseudomenardii*, and is therefore of latest zone T3 age. Most of the formation lies within zones T4 to T6 with the uppermost sections containing *Planorotalites simplex* above the extinction horizon of *P. pseudomenardii*. Data combined from a number of wells indicate that the formation is late Early Paleocene to Late Paleocene in age.

The disconformity at the top of the Dockrell Formation cuts out variable portions of the Upper Paleocene sequence. In wells on the Rankin Platform, zones T7 and part or all of T6 generally are missing (*i.e.* from the extinction level of *Globorotalia chapmani*). In the wells furthest offshore, the amount of missing sequence increases, so that only the lowest zone of the Late Paleocene (zone T4) is present below the disconformity. This distribution of zones, plus the deep-water deposits present (see below), suggests that the disconformity may be a submarine feature.

Environment of deposition

The formation contains abundant foraminifers with planktonic forms in great abundance and diversity. The environment of deposition is inferred to deepen rapidly from middle to outer shelf by the base of zone T4, followed by gradual

deepening to slope depths over the Rankin Platform by later zone T5 time. Accordingly, the basal part of the Dockrell Formation marks the beginning of a rapid sea-level rise (cycle 1B of Apthorpe 1981) as the sea transgressed the North West Shelf for the second time in the Paleocene.

WILCOX FORMATION

(R.S. Heath and M.C. Apthorpe)

Definition

The Wilcox Formation is a Late Paleocene to Middle Eocene argillaceous sequence on the North West Shelf. The type section (Fig. 103) is in Goodwyn 6 between 2132 and 2292 m.

The Wilcox Formation disconformably overlies the Dockrell Formation. The boundary is marked by prominent sonic and gamma-ray log breaks and a variable palaeontological hiatus between the Wilcox Formation and the underlying Dockrell Formation.

In the type section, the Wilcox Formation is disconformably overlain by the Walcott Formation and the boundary is marked by distinct breaks in gamma-ray and sonic-log curves. In other sections, such as in Fisher 1, the upper boundary is commonly transitional into the siltstones of the Walcott Formation, and a precise boundary is difficult to pick.

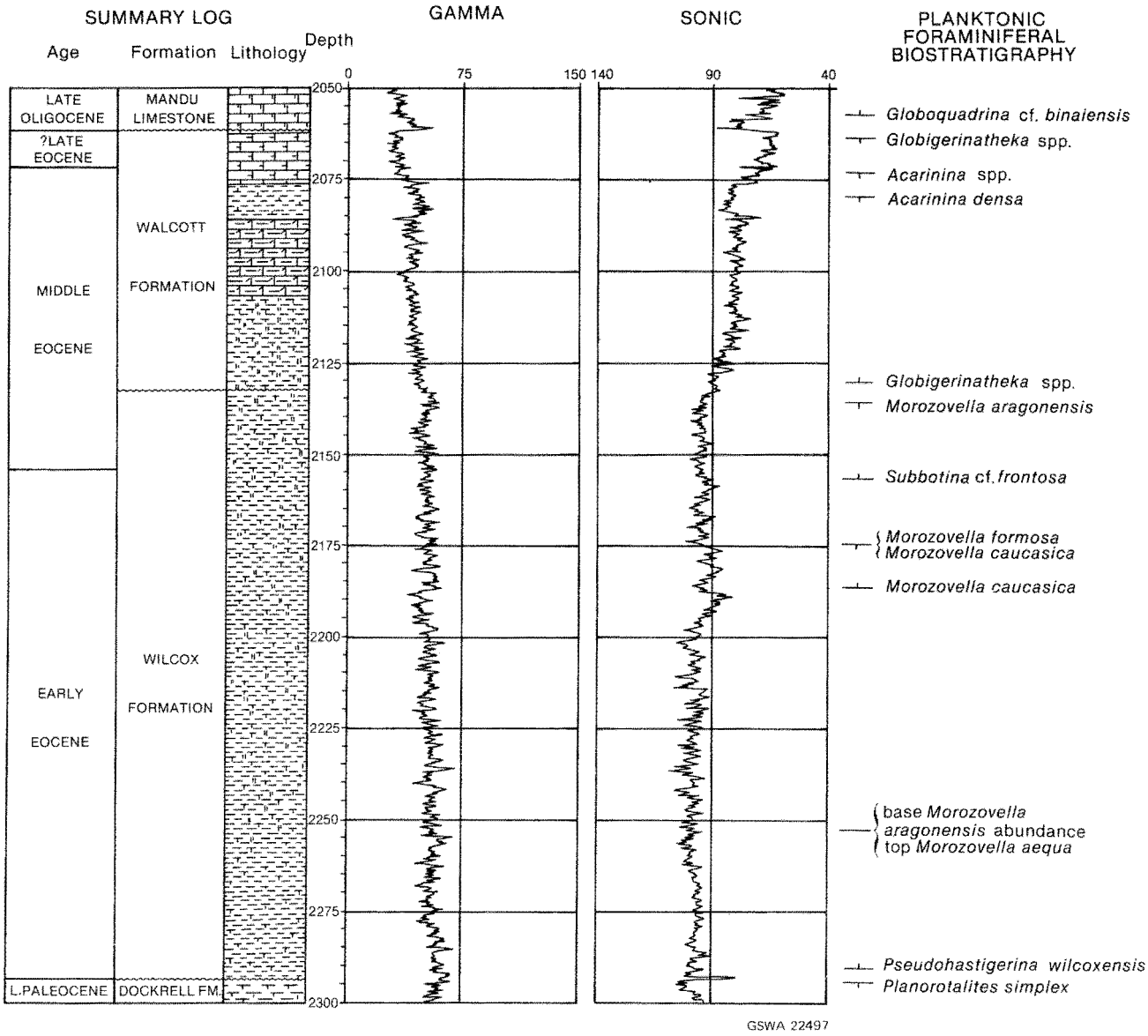

Figure 103. Type sections of the Wilcox and Walcott Formations, Goodwyn 6.

Lithology

The Wilcox Formation consists of olive-grey, grey-green to olive-black, flaky, slightly silty, pyritic and glauconitic claystone, calcareous claystone, and minor silty, pyritic and glauconitic, olive-grey marl. Silty claystone occurs only in the upper three-quarters of the formation in the type section.

Distribution and thickness

The Wilcox Formation occurs over a wide area from Delambre 1 to the Rankin Platform. Some well intersections are Delambre 1, ?1927–1990 m; Fisher 1, 2292–2417 m; Walcott No. 1, 1760–1897 m; Withnell 1, ?954–1002 m. At Withnell 1, there is microfaunal evidence of shallowing of the environment, and it is believed that the formation lenses out to the south of this well.

Fossils and age

In the type section of the Wilcox Formation, planktonic foraminifers indicate an Early Eocene (zone T8 = zone P6b) to early Middle Eocene (zone T10) age (Fig. 103). A few wells contain up to 5 m of latest Paleocene (zone T7 = P6a/Top P5) at the base of the Wilcox Formation, the age being indicated by the overlapping ranges of *Morozovella velascoenisis* and *Pseudohastigerina wilcoxensis (e.g.* in Miller 1 at 2321 m).

Environment of deposition

Planktonic and benthonic foraminifers are present throughout the formation. The relative abundance of foraminiferal taxa indicates deposition within outer-shelf to deep-marine (?slope) conditions over most of the area.

Micropalaeontological analysis of closely spaced sidewall core samples in the type section revealed that distinct changes in assemblages correspond to wireline-log character intervals. These probably represent rapid and distinct climatic fluctuations within an outer shelf-slope environment of deposition. In the type section from 2255 to 2292 m (zone T8 = zone P6b) and 2175 to 2185 m (basal zone T10 = zone P9) well-preserved planktonic foraminifers with abundant *Morozovella* species suggest warm-water conditions. The adjacent intervals from 2185 to 2255 m (zone T9 = zone P7-P8) and 2132 to 2175 m (upper zone T10 = zone P10 contain poorly preserved planktonic foraminifers with low numbers of *Morozovella* species which suggest cooler marine conditions.

Shallower facies of middle-shelf type are suggested by foraminiferal assemblages at Withnell 1, in the south, and by similar assemblages and a sandy lithology at Lewis 1A to the east. South of Withnell 1 the Wilcox Formation is believed to become still shallower in facies and to lens out.

WALCOTT FORMATION
(R. S. Heath and M. C. Apthorpe)

Definition

The Walcott Formation is a deep-water correlative of the Giralia Calcarenite. It is a calcilutite and claystone sequence and lies disconformably on the Wilcox Formation and below the Mandu Formation. The type section is the interval between 2061 and 2132 m in Goodwyn 6 (Fig. 103). The upper part of the formation is better developed in Fisher 1, so that section from 2109 to 2185 m is here considered as a principal reference section (Fig. 104). Correlation between the two sections is provided by the base of a hard calcilutite unit, which is at 2185 m in Fisher 1 and 2076 m in Goodwyn 6.

The boundaries of the Walcott Formation are marked by palaeontological, lithological and wireline-log discontinuities.

Lithology

The formation is divisible into three units on the basis of gamma-ray and sonic logs (Figs 103 and 105).

In Goodwyn 6 the lower unit (between 2085 and 2132 m) consists of light olive-grey, argillaceous calcisiltite with traces of quartz silt and pyrite. Argillaceous content increases with depth. The middle unit, between 2076 and 2085 m, consists of light olive-grey calcareous claystone with traces of glauconite and pyrite. The upper unit occurs between 2061 and 2076 m and is a light-grey to white, hard calcilutite with trace amounts of clay, quartz silt and glauconite. Significant microcrystalline recrystallization has probably occurred.

In Fisher 1, the lower unit (between 2208 and 2292 m) is a grey calcareous siltstone with minor glauconite, and the middle unit (between 2185 and 2208 m), is a light-grey calcareous claystone with up to 30% quartz silt, a trace to 10% glauconite and a trace to 15% foraminifers. The upper unit extends from 2109 and 2185 m and is much thicker and spans a greater time interval than

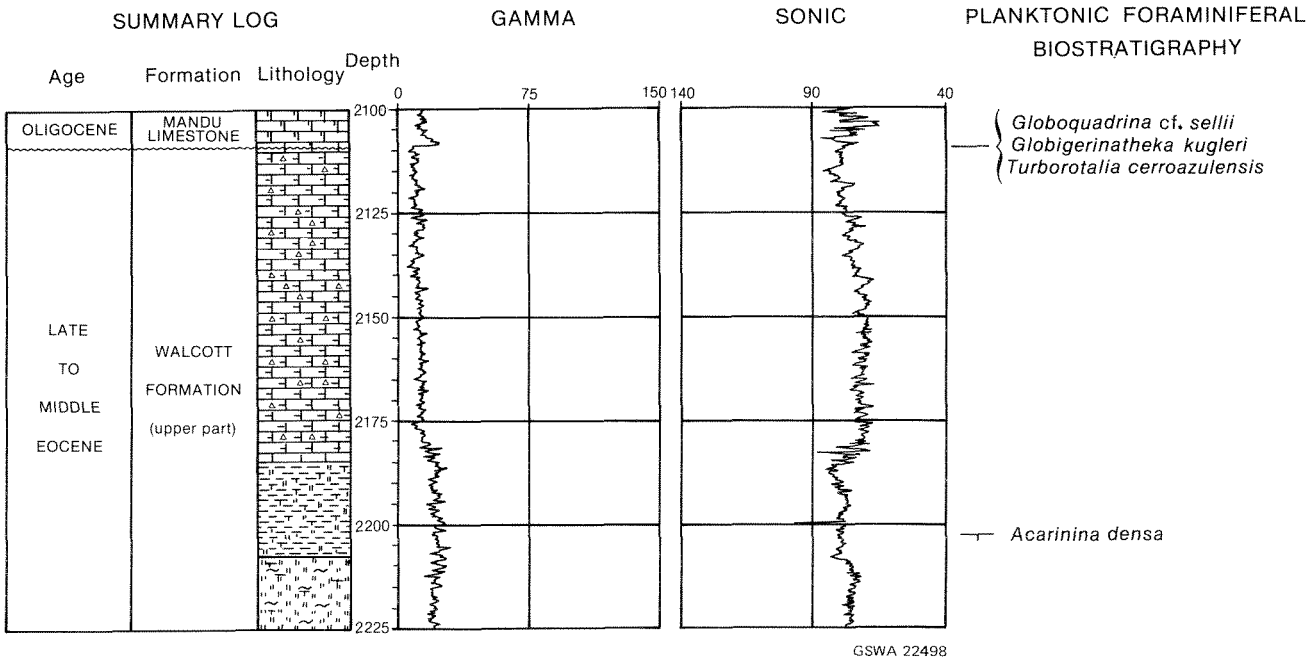

Figure 104. Reference section for the upper part of the Walcott Formation, Fisher 1.

in Goodwyn 6. It consists of white to cream, hard, argillaceous calcilutite with up to 40% interbedded, hard, yellowish-brown cryptocrystalline chert of probable replacement origin. The calcilutite contains up to 30% quartz silt and trace amounts of glauconite.

Distribution and thickness

The Walcott Formation occurs throughout the southern North West Shelf from Brigadier 1 to the Rankin Platform. It grades laterally into the Giralia Calcarenite along the onshore side of the sub-basin, where the water depth was less in wells such as Lewis 1A. In Legendre 1 the Walcott Formation may intertongue with the Giralia Calcarenite.

The maximum thickness of the Walcott Formation is approximately 400 m in Parker 1, compared to 183 m in Fisher 1 and 71 m in Goodwyn 6. Other intersections include: Walcott 1, 1599–1760 m; Miller 1, 2068–2157 m; Brigadier 1, ?2340–2474 m; Lambert 1, 1944–?2070 m. As in the case of Goodwyn No. 6, there is some palaeontological evidence to suggest that the top of the formation may have been eroded in some wells, to variable levels within the Middle Eocene.

Fossils and age

The argillaceous basal section of the Walcott Formation is dated as Middle Eocene, based on the planktonic foraminifers *Globigerinatheka* spp. and *Acarinina* spp.

The preservation of foraminifers in the hard, cherty calcilutite of the upper unit is generally very poor due to extensive recrystallization, and biostratigraphic resolution is coarse. The presence of *Globigerinatheka* spp., together with members of the *Turborotalia cerroazulensis* lineage and *Globoquadrina* cf. *sellii*, and the absence of *Acarinina* spp. suggests a Late Eocene age.

On the eastern side of the Dampier Sub-basin, correlative sections of the Walcott Formation (probably best referred to the Giralia Calcarenite) contain the larger benthonic foraminifers *Discocyclina* and *Lacazinella*. A generalized Middle to Late Eocene age has been suggested in the absence of planktonic index fossils.

Environment of deposition

The Middle Eocene argillaceous calcilutites of the middle and lower units contain diverse assemblages of planktonic foraminifers indicating deposition in at least middle-shelf depths. Relatively warm waters are suggested by the presence of *Hantkenina dumblei*, which is restricted to this lithofacies. Poor preservation of foraminiferal assemblages in the higher cherty-limestone section hampers environmental interpretation. However, the lack of the larger benthonic foraminifers, which are present in correlative sections on the eastern side of the sub-basin, suggests deposition in (at least) middle- to outer-shelf depths.

GIRALIA CALCARENITE

Definition

The Giralia Calcarenite ("Giralia Limestone" of Singleton 1941; amended by Condon and others, 1956) lies disconformably between the Cardabia Calcarenite and the Cape Range Group. The type section is on the west flank of the Giralia Anticline, near No. 10 Bore, (Cardabia) and was measured as 61 m thick by Condon and others (1956). As with the underlying Cardabia Calcarenite, thicknesses of the Giralia Calcarenite are difficult to determine in the Giralia Anticline because of low dips and poor exposure. The Giralia Calcarenite correlates with the Merlinleigh Sandstone, a shallow-marine to continental quartz sandstone from the Merlinleigh Sub-basin, and (probably) the Robe Pisolite, a pisolitic limonite deposit of mixed-continental origin from the Hamersley region, adjoining the northeastern Carnarvon Basin. The Walcott Formation of the Dampier Sub-basin is a deep-water, basinal equivalent.

Lithology

In outcrop, the Giralia Calcarenite is a generally distinctive, yellowish to brownish, or greenish, medium- to coarse-grained, calcarenitic to calciruditic packstone to grainstone. It is commonly quartzose and slightly ferruginized, and in many places contains abundant discoid foraminifers. Other characteristic features are its slightly coarser grain size (compared to surrounding units in outcrop) and the common occurrence (especially near the base) of ferruginized grains.

Most of the ferruginous grains infill tests of foraminifers and other microfossils but some are structureless, rounded pellets of ?limonite/goethite. Glauconite pellets and ?chamosite ooliths of the same size are also present, as are traces of ?glauconite in some foraminiferal tests. Contemporaneous primary deposition of glauconite and chamosite probably occurred, both as pellets and in porous fossils, with later alteration to limonite and/or goethite. Such infilling and replacement are known from greensands (Pettijohn and others, 1973, p. 228). Syndepositional reworking of this material into intraclasts produced a pebbly layer at the base of the formation. Conversion of chamosite and glauconite to limonite/goethite may have occurred much later. This ferruginous conglomerate locally provides a useful marker bed in outcrop, distinguishing the Giralia Calcarenite from the upper Cardabia Calcarenite.

Condon and others (1956) distinguished an upper and a lower unit, sometimes interbedded, in the Giralia anticline but these have not been recognized in the present study, possibly because of the more regional nature of the mapping.

Distribution and thickness

The Giralia Calcarenite is preserved over much of the Carnarvon Basin, and is exposed in the Giralia and Cape Cuvier Anticlines, on Barrow Island, and on Yaringa and Wooramel Stations near the mouth of the Wooramel River. In the southern Carnarvon Basin, it is recognized in Dirk Hartog 17B (69 m), Edel 1 (78 m), and several water bores, the most easterly of which is Woodleigh 4. In the outcrops on Yaringa and Wooramel Stations, it is less than 10 m thick, and appears to have filled erosional hollows cut in the top of the Toolonga Calcilutite.

The formation appears to be absent between the Wooramel and Gascoyne Rivers. If deposited, it was eroded prior to the Miocene. North of the Gascoyne River, the Giralia Calcarenite is recorded in Bibbawarra Bore (3 m), and thickens to the north and west (Denman and van de Graaff, 1982). In some of the coastal anticlines, pre-Miocene erosion, probably associated with the initial stages of formation of the anticlines, has removed the Giralia Calcarenite.

In the Giralia Anticline, the Giralia Calcarenite is about 60 m thick. North and west of this, it is absent in some petroleum-exploration wells, and is not differentiated in many others. From the limited data, thickness appears quite variable, with a maximum of 226 m in Rough Range South 1. Although 142 m is recorded in Cape Range 1, the Giralia Calcarenite is absent beneath Exmouth Gulf and between West Murion 1 and Onslow 1. It apparently thickens rapidly north of Locker 1 (where it is absent) to 122 m in Long Island 1, but is absent further to the north in Hilda 1A. These variations in thickness, in an essentially offshore area, suggest that the present distribution of the unit may be controlled by post-Eocene erosion.

Fossils and age

The Giralia Calcarenite is richly fossiliferous; with a fauna including foraminifers, terebratulid brachiopods, nautiloids, echinoids, bivalves, gastropods, bryozoans, fish teeth, and crustacean fragments (Condon and others, 1956). A Middle to Late Eocene is well established (Condon and others, 1956; Cockbain, 1981), with Ludbrook

(1967) favouring a Late Eocene age. Quilty (1974) considered that the Giralia Calcarenite and its offshore time-equivalents range in age from Tertiary P10 to P16.

Environment of deposition

In outcrop areas, the coarse-grained packstones and grainstones indicate a high-energy environment on an open-marine shelf, probably with subtidal shoaling, while the presence of glauconite pellets, fish teeth, and possible chamosite ooliths suggests shallow water with slow deposition. As with other Tertiary carbonate units, deepening occurred to the north of the Giralia Anticline and west of the present-day coastline.

MERLINLEIGH SANDSTONE

Definition

The Merlinleigh Sandstone was named by Teichert (1950) and defined by Condon (1954). The type section is in the west side of a mesa approximately 1 km east-southeast of the ruins of Merlinleigh homestead, from which the name is derived.

The Merlinleigh Sandstone is a shallow-marine (?littoral) to continental, siliciclastic correlative of the Giralia Calcarenite and (probably) the Robe Pisolite. It rests unconformably on Permian and Cretaceous rocks, and in most exposures forms caps to mesas or plateaus.

Lithology

The dominant rock type in the Merlinleigh Sandstone is coarse- to very coarse-grained sandstone. Lesser amounts of medium- to fine-grained (commonly silty) sandstone, siltstone, pebble and granule conglomerate, and minor claystone also occur. The base of the formation is in places marked by a pebble to boulder conglomerate lag deposit, with small erosional hollows cut into the underlying rocks. The sandstone is dominantly quartz wacke, with lesser quartz arenite and feldspathic wacke, but subsequent duricrusting commonly masks the unit and alters its appearance, rendering compositional and fabric descriptions unreliable. Sorting varies from poor to moderate, and rounding from angular to sub-rounded.

Planar cross-bedding is prominent, but significant amounts of trough cross-bedding and (especially in finer grained parts of the formation) planar bedding are present. Palaeocurrents were dominantly northwards to northwestwards although eastwards-dipping foresets occur at several localities.

Where the Merlinleigh Sandstone is relatively thin, duricrusting locally obliterates features and makes identification difficult. Over much of the southern part of Kennedy Range, for example, it cannot be determined whether the unit is present and completely masked by duricrusting, or whether it is absent and a local lag deposit has been duricrusted.

Distribution and thickness

The main outcrop area of the Merlinleigh Sandstone is on the top of Kennedy Range. Elsewhere, isolated outcrops extend as far as Mardathuna homestead to the west, Moogooloo Hill to the northwest, and the Lyndon River to the north. Although Condon (1965, 1962b) showed the Merlinleigh Sandstone extending as far south as the low scarps on the northwestern side of the Carrandibby Inlier, remapping during the present study (Denman and others, 1985; Williams, Williams and Hocking, 1983) assigned outcrops south of the Gascoyne River to the Pindilya Formation. This is because they appear to be laterally continuous with outcrops of the Pindilya Formation in the Wooramel River area, and are separated from the main area of the Merlinleigh Sandstone by the Gascoyne River drainage. The possibility does remain, however, that they are Merlinleigh Sandstone, because the two units occupy similar morphostratigraphic positions and are of similar appearance.

The type section of the Merlinleigh Sandstone is approximately 9 m thick as measured by Condon (1954); another section in the same mesa is 6.6 m thick. Elsewhere the Merlinleigh Sandstone is a maximum of 15 m thick (Condon, 1967) and rarely exceeds 10 m. Thickness is commonly difficult to determine because of subsequent lateritization and silcretization.

Fossils and age

Fossils are only present in the Merlinleigh Sandstone at some localities and horizons, but a rich variety of bivalves, gastropods, echinoids, foraminifers, corals, nautiloids, hydrozoans, bryozoans, wood, and leaves have been found. McNamara and Scott (1983) described fossil banksia fruits from the type area.

Glenister and others, 1956, Glenister and Glover (1958), and Ludbrook (1967) considered the Merlinleigh Sandstone to be of Middle to Late

Eocene age, most probably Late Eocene. This is supported by the echinoids (Brunnschweiler, 1961) and foraminifers (Cockbain, 1981).

Environments of deposition

The silty matrix and northwesterly palaeocurrents, common in many outcrops of the Merlinleigh Sandstone, suggest that most of the unit was deposited in a fluvial environment. However, the fossils clearly indicate a marine setting, and a nearshore to coastal (possibly in part lagoonal) setting is envisaged, with little terrigenous sediment escaping to the fully marine shelf on which the Giralia Calcarenite was deposited.

ROBE PISOLITE

The Robe Pisolite (de la Hunty, 1965) is a pisolitic limonite which occurs over much of the Hamersley Basin in major-drainage depressions. Before 1965, the pisolite had been included within the Poondano Formation, an equivalent unit which outcrops in the Port Hedland area (Harms and Morgan, 1964). While not known in the Carnarvon Basin, outcrops of Robe Pisolite are marginal to the Carnarvon Basin, and are probably coeval with the Giralia Calcarenite and Merlinleigh Sandstone. The unit is therefore briefly described here.

The type section is east of Deepdale homestead in the north face of a large mesa on the south bank of the Robe River. It consists of 12 m of coarse-grained, red, ochreous pisolite overlain by 3 m of fine-grained, locally vitreous pisolite. The top surface is eroded and the base is obscured. Directly to the east the unit overlies the Precambrian Marra Mamba Iron Formation.

The lithology of the Robe Pisolite was described in detail by MacLeod (1966) and Harms and Morgan (1964). It consists of limonitic and hematitic pisoliths with variable (but generally small) amounts of terrigenous material and scattered fragments of fossil wood. Analyses of the pisolite show iron (Fe) content ranges as high as 60%, and is commonly greater than 50% in higher grade ore zones (MacLeod, 1966, p. 139).

The formation is up to 45 m thick, but generally about 15 m thick, and in outcrop it varies from elevated terrace remnants and mesas (as in the type area) to locally subcropping valley fill. The distribution of the Robe Pisolite clearly outlines palaeodrainages, in particular the ancestral Robe River.

Four hypotheses have been advanced to explain the origin of the pisolite:

(a) direct chemical precipitation as bog iron ore;

(b) replacement and desilicification of jaspilitic debris in fluvial sediments;

(c) clastic accumulation as fluvial sediments;

(d) lateritization of fluvial sediments

These were discussed fully by MacLeod (1966) and Harms and Morgan (1964), but no firm conclusions were reached. We suspect that no single mechanism can adequately explain the pisolite throughout its whole extent.

The Robe Pisolite is probably of Late Eocene age. No palaeontological evidence for age is known from the unit itself, but a microflora of late Early Eocene to early Late Eocene age is present immediately beneath the pisolite in boreholes on MOUNT BRUCE (Backhouse, 1979).

CAPE RANGE GROUP

The Cape Range Group was defined by Condon and others (1953) to include the Mandu Limestone, Tulki Limestone and Trealla Limestone. Later, Condon (1968) amended the group to exclude the Trealla Limestone. Van de Graaff and others (1980) reinstated the Trealla Limestone within the Cape Range Group, and included the Pilgramunna Formation, Vlaming Sandstone, Bullara Limestone, and Lamont Sandstone, because together these form a single, unconformity bounded, depositional unit in the Carnarvon Basin. An eighth formation, the Bare Formation from the Dampier Sub-basin and Rankin Platform, is here included in the Cape Range Group.

A disconformity is present beneath the Trealla Limestone, spanning zone N7 and possibly parts of N6 and N8 (Quilty, 1974). However, because the formations above and below the disconformity clearly form a single, major, depositional sequence, they are all placed in the Cape Range Group. Detailed work in the future may necessitate reinstatement of the "Yardie Group" (Condon and others, 1955), as a subgroup within the Cape Range Group, for the sediments above the disconformity.

MANDU LIMESTONE

Definition

The Mandu Limestone of Condon and others, 1953; ("Mandu Calcarenite" of Condon, 1954; amended by Hocking, 1985) disconformably overlies the Giralia Calcarenite or Walcott Formation and is overlain conformably by the Tulki Limestone in the Cape Range area or disconformably by the Trealla Limestone elsewhere. The type section (in which the base of the Mandu Calcarenite is not exposed), is on the south side of Badjirrajirra Creek and is 76 m thick (Fig. 105). The interval between 1590 and 2061 m in Goodwyn (Fig. 106) provides a reference section for the Rankin Trend area.

The name is changed back to the original name for two reasons. Firstly, much of the formation is a calcisiltite or calcilutite, and secondly, north from the outer Dampier Sub-basin (*e.g.* Lambert 1), the formation shows a progressive northwards fining to calicisiltite and then to marl. The less specific term "limestone", rather than "calcarenite", allows for such lithological variation.

Lithology

In the Cape Range area the Mandu Limestone consists of friable, largely impermeable, white to cream, chalky to marly calcarenite, calcisiltite and calcilutite. The calcarenite ranges from packstone to wackestone, and the grains are mainly bioclastic, with moderate amounts of quartz. Terrigenous content is up to 25% and is mostly clay. The formation is typically thin to medium bedded and contains occasional bands of flint nodules and chalcedonic concretions, some of which are geodes. Bioturbation has largely destroyed the bedding, and recognizable trace fossils are present but not common. A characteristic feature of the unit is beds and lenses of large lepidocyclinid foraminifers, commonly well imbricated, which probably accumulated during storms.

North of Cape Range, the grain size of the Mandu Limestone decreases and calcilutite becomes dominant. Quilty (1974) noted that in the North Tryal Rocks area, the entire Cape Range Group consists of marl, chalk, and calcarenite, with no clear lithological distinction between units within the group.

Heath and Apthorpe (written comm.) state that, in the Dampier Sub-basin and Rankin Platform:

"The lower (Oligocene) portion of the Mandu Limestone is a light grey to light olive-grey calcisiltite, consisting predominantly of 'smaller' benthonic foraminifers, with lesser finely abraded biogenic debris, 5% quartz silt and traces of glauconite and pyrite. These components are grain-supporting, in a subordinate matrix of calcilutite. In some wells, crystalline calcite cement is locally present in place of the calcilutite matrix.

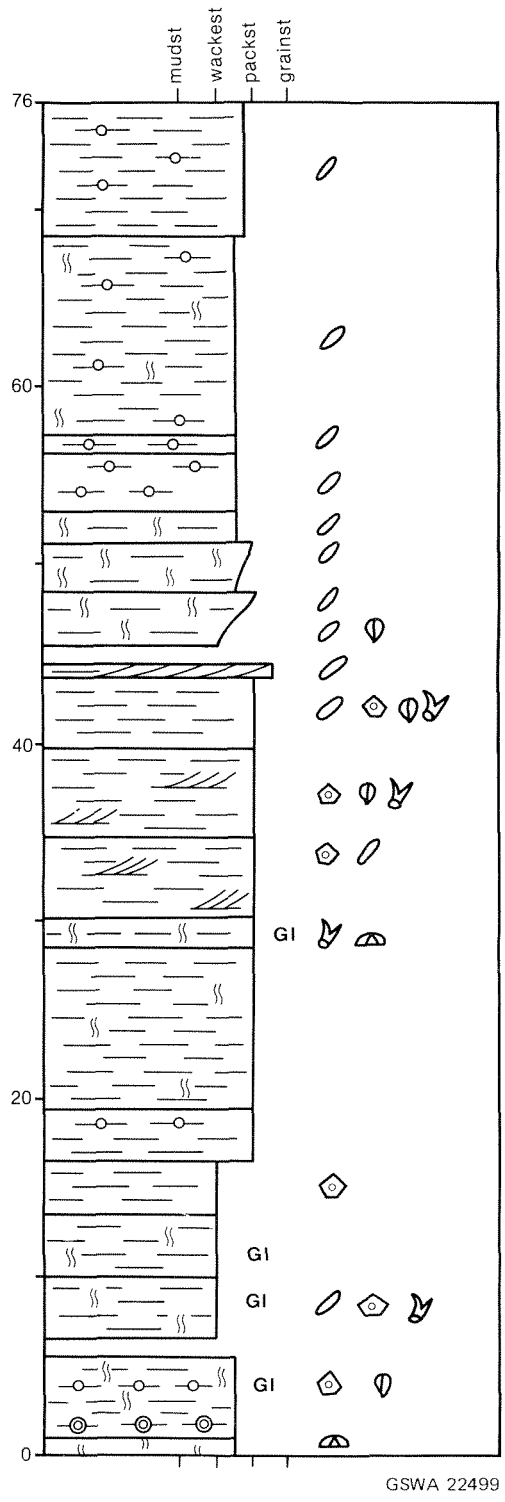

Figure 105. Mandu Limestone type section. See text for discussion of upper boundary.

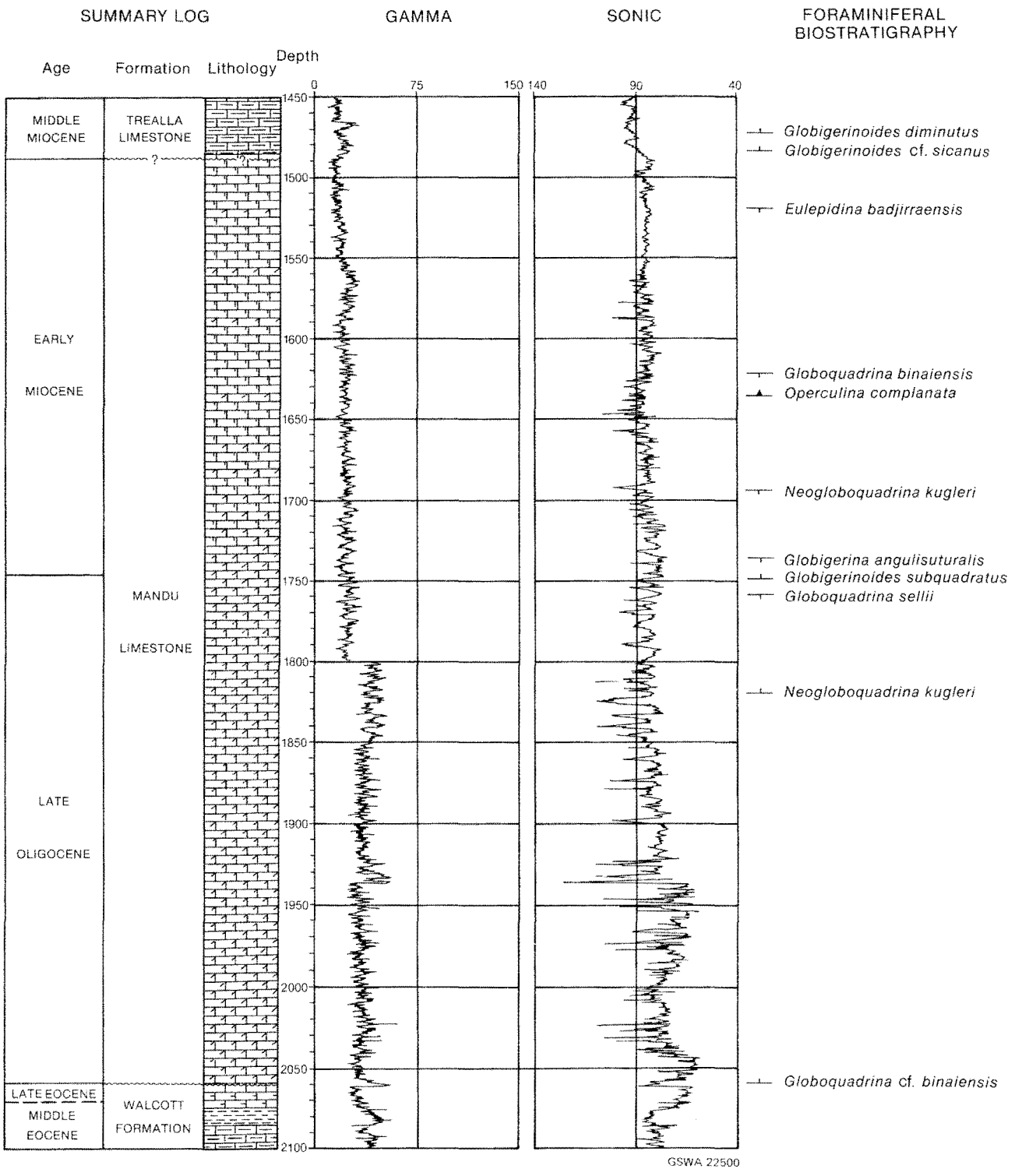

Figure 106. Reference section for Mandu Limestone on Rankin Trend, in Goodwyn 6.

"The higher (Miocene) portion is a light grey to white calcisiltite to calcarenite. The grain size of the foraminifers, algae, shell fragments and unidentifiable biogenic grains increases upward to coarse-grained in some samples. Poor sorting and a calcilutite matrix continue to be characteristic.

"On the outer edge of the North West Shelf, in Brigadier 1 and Delambre 1, the formation is an olive-grey marl, in which the only grains above clay size are planktonic foraminifers."

Distribution and thickness

The Mandu Limestone is present throughout the Barrow and Dampier Sub-basins. In the Exmouth Sub-basin, it is present except in the extreme southeastern corner, near Rough Range.

The Mandu Limestone is 278 m thick in Cape Range 2. North of Cape Range, it thickens markedly, (Quilty, 1974). Although the Cape Range Group is not subdivided in most wells, the Mandu

Limestone appears to be commonly more than 300 m thick. It thickens over the Rankin Platform, with 724 m in Pueblo 1, 571 m in Goodwyn 6, and 596 m in Fisher 1.

From Brigadier 1 northeast to Delambre 1, the wedge of calcisiltite thins from 153 m to a marl 19 m thick which is rich in planktonic foraminifers.

Fossils and age

The Mandu Limestone is richly fossiliferous in outcrop, with large lepidocyclinid foraminifers (including *Lepidocyclina (Eulepidina) badjirraensis*) and *Operculina complanata*, bivalves, echinoids, bryozoans, sponges, and crustacean fragments.

The base of the Mandu Limestone is early Late Oligocene (foraminiferal zone N2), locally extending down to zone P19/20 or up to N3, (Quilty, 1974, 1980; Chaproniere, 1984; Heath and Apthorpe, written comm.). The top of the formation is Early Miocene (N5, locally N6) (Chaproniere, 1984; Heath and Apthorpe, written comm.).

Environment of deposition

The Mandu Limestone is a shallowing-upward sequence. In the Cape Range area, Chaproniere (1975) considered that the lower Mandu Limestone was deposited in quiet, open-shelf conditions with normal oceanic salinities at a depth of approximately 120 m. The water depth gradually decreased, to perhaps as little as 12 m, because a rich shallow-water biota is present in packstones of the upper Mandu Limestone (Chaproniere, 1975). However, the energy level of the environment remained low, and Chaproniere suggested that this may have been due to a widespread sea-grass baffle which trapped mud and inhibited wave action. The beds of large foraminifers probably accumulated largely as storm-generated shoals.

In the Dampier Sub-basin, the lower half of the formation contains abundant planktonic foraminifers together with the *Cyclammina* sp. The sea became progressively deeper to the north. Quilty (1974) interpreted outer-shelf conditions north and west of Tryal Rocks 1. Heath and Apthorpe (written comm.) state: "deposition of the lower half of the formation occurred in a shelf-edge/slope environment. The upper part of the formation is dominated by benthonic species with abundant larger foraminifers, and was deposited in an inner to middle shelf environment. This shallowing-upward sequence is consistent with the model of a prograding carbonate shelf (Apthorpe, 1981). Westerly-prograding sigmoidal reflections, with a relief often in excess of 300 m, are seen on seismic sections. Each sigmoidal reflection marks the position of the shelf-edge/slope at a point in Late Oligocene–Early Miocene time".

BULLARA LIMESTONE

Definition

The Bullara Limestone (Chaproniere, 1975, 1976) is a lateral equivalent of the lower part of the Mandu Calcarenite which has been recognized only in the Rough Range area. It is coarser grained and cleaner than the Mandu Limestone and contains a different fauna. The type section is in Rough Range South 1 between 220 and 306 m. the unit is unconformable between the Giralia Calcarenite and the Trealla Limestone.

Lithology

The Bullara Limestone consists of poorly to moderately well-sorted, medium- to coarse-grained, bioclastic foraminiferal grainstone with some packstone. The packstone is cleaner than equivalent sediments in the Mandu Limestone, which grade from packstone to wackestone. In the type section below 274 m, the unit is medium grained, grading into coarse-grained sediments containing algal nodules and larger foraminifers above 274 m. The top of the Bullara Limestone is almost wholly recrystallized, and alteration progressively lessens down the sequence.

Distribution and thickness

Exposure is restricted to the bottom of a few gullies on the crest of the Rough Range Anticline near Rough Range 5. These outcrops were previously interpreted as Tulki Limestone by Condon and others (1953, 1955) and Mandu Limestone by Condon (1968). It was intersected in Exmouth 1 between 119 and 159 m, Exmouth 2 between 167 and 250 m, and Learmonth 2 between 215 and 349 m (Chaproniere, 1976). Some Eocene foraminifers are present in the lower part of the Bullara Limestone, and the lack of supporting evidence for an Eocene age suggests that these were reworked from subaerially exposed Giralia Calcarenite (Chaproniere, 1975). This would presumably have been in the Giralia Anticline, which restricts the eastwards extent of the Bullara Limestone.

Fossils and age

Chaproniere (1975, 1976, 1984) dated the Bullara Limestone as Late Oligocene (zone N3 to N4, or lower "e" stage). The unit contains a varied, shallow-water fauna.

Environment and deposition

On faunal grounds, Chaproniere (1975) concluded that the Bullara Limestone was deposited in a high-energy marine environment at a depth less than 30 m, and possibly less than 20 m. The environment shallowed during deposition of the unit. A near-shore shoaling environment seems probable, with shoals forming on and around seagrass banks and being constantly reworked by waves. Any terrigenous mud carried into this environment was not deposited because of the high-energy conditions, and instead was carried to deeper, quieter areas where the Mandu Limestone formed.

The high-energy facies represented by the Bullara Limestone is only found in the Rough Range area probably because uplift of the Giralia Anticline, a short distance to the southeast, commenced earlier than elsewhere. This uplift provided a sufficiently steep gradient in the coastal zone to allow wave action rather than tide action to dominate.

TULKI LIMESTONE

Definition

The Tulki Limestone (Condon and others, 1953) is recognized only in the Cape Range area. In most of the offshore area, only two major divisions of the Cape Range Group are recognized, and these are "... referred somewhat loosely to the Mandu Calcarenite and Trealla Limestone" (Quilty, 1974, p. 311). The Tulki Limestone rests conformably on the Mandu Calcarenite, and is disconformably overlain by Trealla Limestone, with a type section on the south side of Badjirrajirra Creek (Fig. 107). Chaproniere (1984) described the contacts in some detail.

Lithology

The Tulki Limestone consists of coarse-grained calcarenitic, muddy foraminiferal packstone and mud-free grainstone which is locally associated with low-angle cross-bedding, suggesting clastic deposition on shoals or banks. The formation is characteristically reddish to yel-

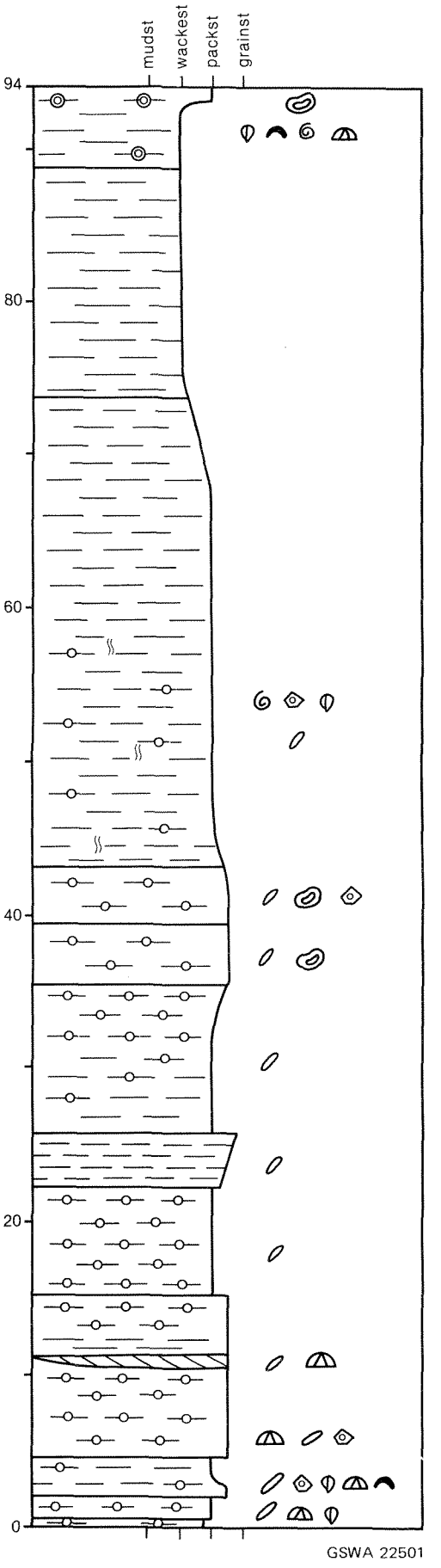

Figure 107. Tulki Limestone type section, south side of Badjirrajirra Creek.

lowish, and Chaproniere (1975, p. 47) stated that this was "produced by red soil particles and fossils, derived by subaerial erosion from an adjacent coastline". This coastline was probably the western flank of the Giralia Anticline, which was then in the initial stages of formation.

On the east flank of Cape Range the Tulki Limestone can be divided into two unnamed members. The lower one, about 30 m thick, comprises a basal transitional unit, a red nodular unit rich in foraminifers and echinoids, and a thin bedded unit with low-angle cross-bedding at the top (Fig. 108). This is overlain with a sharp contact by the upper member, about 65 m thick, consisting of a thinly bedded unit underlying a red nodular unit rich in algal nodules. In turn this is overlain by a thick- to massive-bedded sequence which is commonly recrystallized and forms cliffs in the top 20 m. On the west flank of Cape Range the formation appears to be more uniform, comprising mainly yellowish to red nodular-bedded foraminiferal packstone. It also forms cliffs in the upper part.

The top of the Tulki Limestone was recorded by Condon and others (1953, p. 25) as "a thin band of pisolitic ferruginous limestone which appears to have resulted from the weathering of the limestone". Field study of this contact and of the Trealla Limestone type section showed that ferruginous calcarenite occurs discontinuously along bedding-plane cracks and joints throughout the Trealla Limestone. They do not mark a depositional and erosional break between the two formations but are much younger phenomena. However, the uppermost Tulki Limestone is commonly highly recrystallized (Chaproniere, 1975, 1984) whereas the Trealla Limestone is not. This supports the foraminiferal evidence for a disconformity between the Tulki and Trealla Limestones put forward by Quilty (1974) and Chaproniere (1984).

Distribution and thickness

The Tulki Limestone is present only in the Cape Range area. Condon and others (1953) stated that the type section was 66 m thick, but remeasuring indicates this figure is incorrect. Examination of the Mandu Limestone and Tulki Limestone at their type sections and other outcrops suggests that the base of the Tulki Limestone, which was taken by Condon and others (1953) at the sharp base of a prominent calcarenite bed, is 10 to 15 m above the top of the Mandu Limestone and the contact is in fact a transitional sequence. The slight angular unconformity interpreted by Condon and others (1953) is considered to be a local erosive contact of no regional significance. Van de Graaff and others (1980) gave 95 m as the revised thickness of the Tulki Limestone type section.

Condon and others (1953) recorded a Tulki Limestone section 127 m thick in Mandu Mandu Creek on the west side of Cape Range. This section was remeasured and found to be about 91 m thick. The description given by Condon and others (1953) indicates their section was measured along the creek bed for a distance of 6 km, which renders their thickness unreliable, particularly because

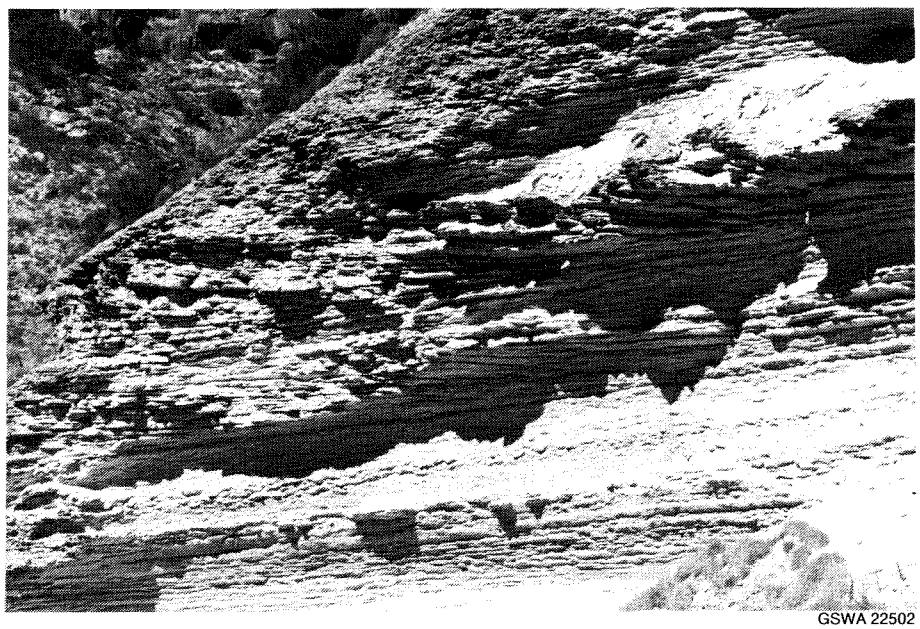

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Figure 108. Tulki Limestone, Badjirrajirra Creek. Indistinct low-angle cross-bedding, dipping to right, can be seen in central portion of picture. Nodular appearance of outcrop is typical of the Tulki Limestone.

bedding in the Tulki Limestone in discontinuous and irregular. Additionally, we consider that the lowest part of the succession exposed is not Mandu Limestone but lower Tulki Limestone. Thus, the thickness figures given by Condon and others (1953) for the two sections on the east and west sides of Cape Range are not comparable. Chapronierе's (1984) conclusions on the degree of erosion after deposition may also be in doubt, as they are based on the figures given by Condon and others.

Fossils and age

The Tulki Limestone fauna is dominated by foraminifers described by Crespin (1953, 1955) and by Chapronierе (1975, 1984), who assigned the unit an Early Miocene (N6 to ?N8) age. Echinoids are common, and crustaceans, gastropods, bryozoans, bivalves, and nautiloids are also present.

Environment of deposition

The Tulki Limestone is a locally developed, shallow-water equivalent of the upper Mandu Limestone. It contains low-angle cross-bedding, which suggests moderate-energy clastic deposition on shoals or banks. Chapronierе (1975) considered that packstones in the Tulki Limestone were deposited in water about 12 m or less in depth, by comparison with faunal and lithological associations in Shark Bay described by Davies (1970). The coarsening-upward sequence from Mandu Limestone wackestones to Tulki Limestone packstones and grainstones in Cape Range supports this interpretation of shallow-water deposition with corresponding higher energy.

TREALLA LIMESTONE

Definition

The Trealla Limestone (Condon and others, 1953) has its type section on the north side of Mount Lefroy (previously Mount Trealla) where it is 48 m thick, with an eroded top (Fig. 109). The unit is disconformable on older rocks. Condon (1968) excluded the Trealla Limestone from the Cape Range Group, because of its widespread distribution compared with the Tulki Limestone or Mandu Limestone, but it was reinstated by van de Graaff and others (1980).

In Cape Range, the uppermost Tulki Limestone and lower Trealla Limestone are difficult to distinguish because they have very similar (if not identical) appearances and faunas, as noted by Chapronierе (1975). During mapping, the boundary was taken at the base of thinly bedded limestone which directly overlies the massive recrystallized facies of the Tulki Limestone. Away from the gorges, the base of the Trealla Limestone is mapped immediately below the lowest occurrence of compound corals, which are fairly common in the Trealla Limestone on Cape Range. Such corals have been observed within 5 m of massive recrystallized limestone, assumed to be Tulki Limestone. In the offshore areas near North Tryal Rocks, the two units recognized, the Mandu Limestone and Trealla Limestone, are similarly difficult to distinguish (Quilty, 1974).

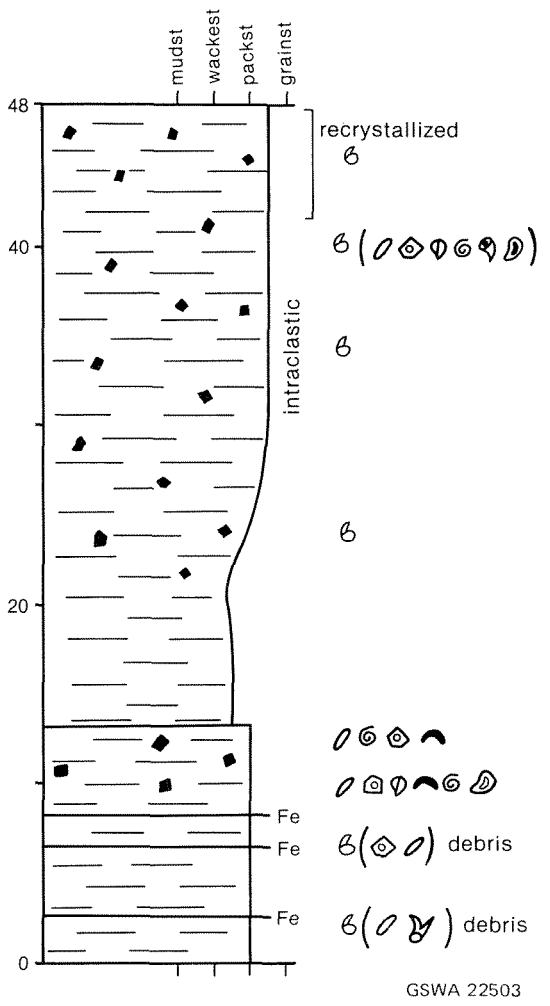


Figure 109. Trealla Limestone type section.

Northeast of the Barrow Sub-basin, Heath and Apthorpe (written comm.) note that:

"The Trealla Limestone grades upwards into the Bare Formation (where present), or is disconformably overlain by the Delambre Formation, with the possible exception of the section in Delambre 1 where the Delambre Formation appears to be conformable on the Trealla Limestone.

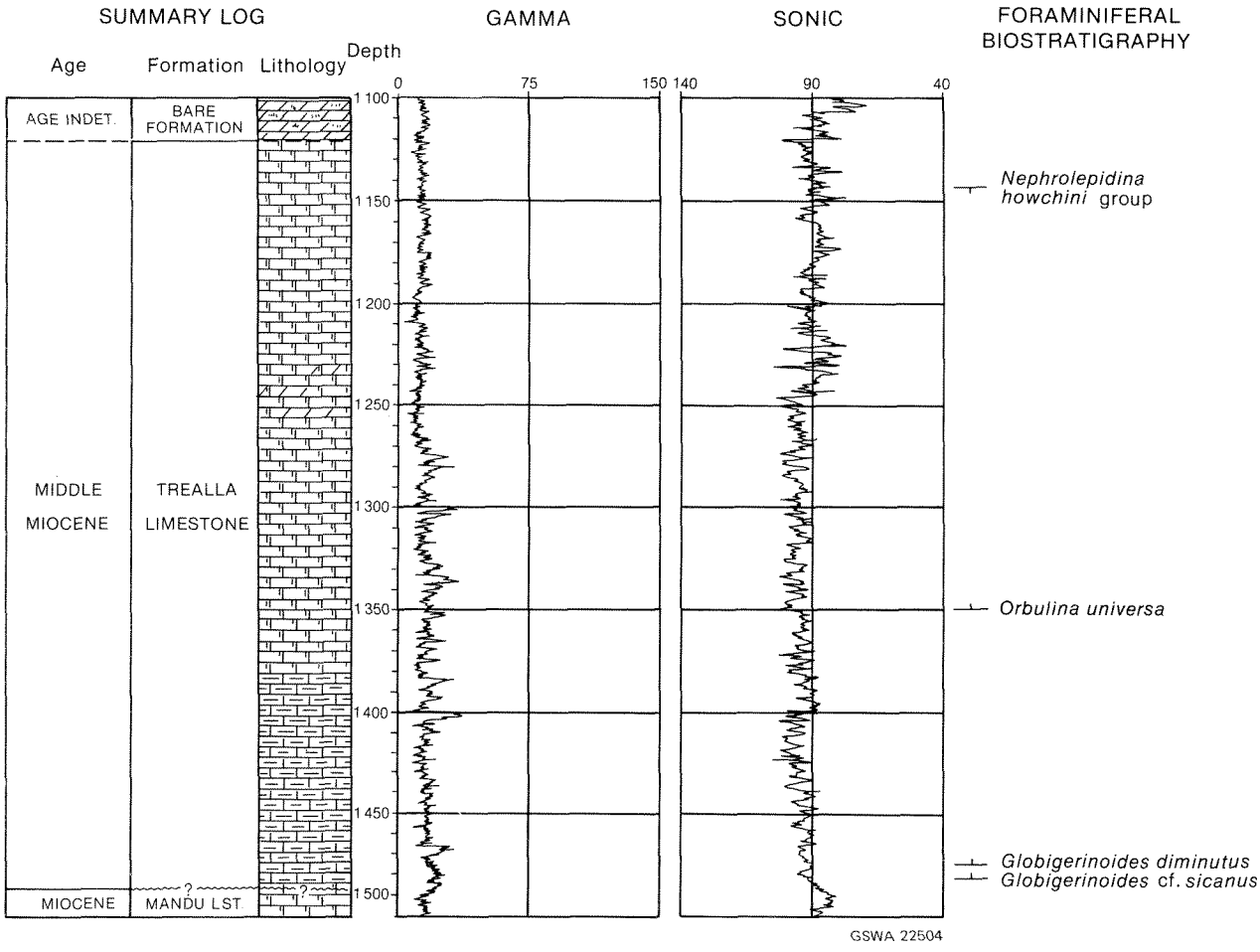


Figure 110. Trealla Limestone reference section on Rankin Trend, Goodwyn 6.

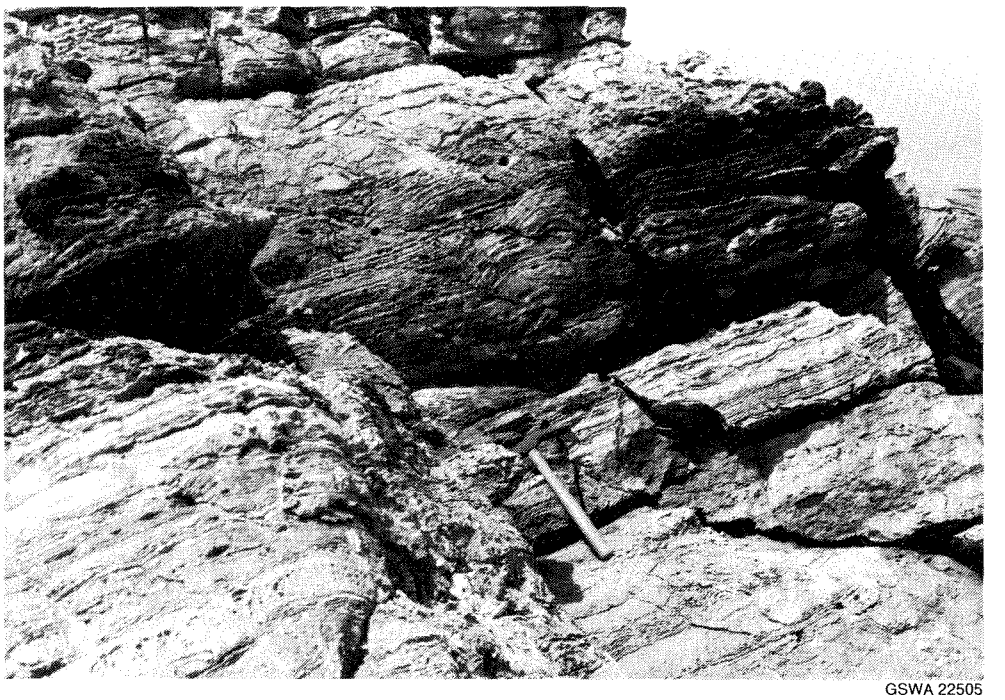
A reference section for the southern North West Shelf is the section in Goodwyn 6 between about 1120 and 1490 m (Fig. 110). The upper boundary of this section is placed somewhat arbitrarily at the top of a massive calcarenite interval, with overlying dolomite being regarded as the basal part of the Bare Formation.

"Time-equivalent facies of the Trealla Limestone rich in planktonic foraminifers are present in Brigadier 1 and Delambre 1 where they disconformably overlie a pelagic facies of the Mandu Limestone."

Lithology

In most onshore areas, the Trealla Limestone is a relatively pure and commonly shelly, white to cream bioclastic packstone to grainstone. Chaproniere (1975) divided the Trealla Limestone of the Cape Range and Rough Range area into a lower unit and an upper unit. The lower unit, mainly restricted to the Cape Range area, is dominantly packstone and is very similar to the uppermost Tulki Limestone. It contains finely banded dolomitic micrite interpreted as algal-mat deposits, and crops out discontinuously on the east side of Cape Range. These are surficially silicified and ferruginized, and are commonly intensely contorted and brecciated, indicating contemporaneous slumping (Fig. 111). The upper unit is more widely distributed and consists mainly of coarse-grained calcarenitic grainstone containing *in situ* compound corals, coralgal boundstone and pockets of shell fragments. The presence of two units in the Trealla Limestone was first recognized, as an upper and lower foraminiferal assemblage, by Crespin (1948, 1950, 1953).

In the Giralia Anticline, the Trealla Limestone contains small but noticeable amounts of disseminated quartz sand, reflecting proximity to the shoreline. Quartz sand is also present in the Rough Range Anticline, where there is a thin laterally persistent unit of quartzose calcarenite. This occurs about 12 m above a 10 m thick zone of reworked Bullara Limestone fossils and is commonly 20 to 30 cm thick (maximum 3 m). In the lower 13 m of the section at Cape Cuvier, the Trealla Limestone contains two thin red, ?soil-derived units and laminated "birdseye" dolomite (Denman and van de Graaff, 1982), of probable lagoonal origin; and northeast of South Lyndon Wells on the north bank of the Lyndon River, sandy and clayey limestones may also be lagoonal.



GSWA 22505

Figure 111. Trealla Limestone, southwest of Exmouth. Algal banding, brecciated due to slumping in foreground, is highlighted by secondary silicification. Dip is depositional, not tectonic.

Immediately east of the North West Coastal Highway near Yaringa, a 10 m thick section of barren, light-grey, limy mudstone containing up to 10% quartz sand grains is exposed in a road-gravel quarry. At Yaringa homestead, 5 km north at the same level, a wackestone containing miliolid and rotaliid foraminifers is present. Both deposits are considered to be lacustrine or lagoonal equivalents of the Trealla Limestone (Denman and others, 1985).

Heath and Apthorpe (written comm.) state: "The Trealla Limestone in the Dampier Sub-basin is a white to cream to greenish-grey, bioclastic calcarenite with traces of pyrite and glauconite and up to 15% calcite cement. Grain size is dominantly medium to coarse but ranges from very fine to very coarse. Skeletal fragments are mostly foraminifers, with subordinate calcareous algae, shell fragments, rare bryozoans and ostracods from unidentifiable biogenic debris. The unit ranges from soft to moderately hard, and is finer grained north and west of the Rankin Platform. Unlike the Mandu Limestone, intermediate facies have seldom been intersected between the extremes of the coarse-grained, shallow-water deposits of the Dampier Sub-basin, and the fine-grained pelagic marls of deep water wells such as Delambre 1 and Brigadier 1."

Distribution and thickness

The Trealla Limestone is the most widespread unit of the Cape Range Group, having been recognized as far south as the Yaringa area, and as far southeast as Woodleigh 4 water bore. It is present in all the coastal anticlines north of 25°S, and east of the outcrop area was intersected by Cunaloo 1 and Minderoo 1. Offshore, the Trealla Limestone has been recognized in all petroleum-exploration wells in which the Cainozoic section has been subdivided.

In onshore areas, the Trealla Limestone is generally about 20 m thick, with a minimum of 6 m in Cunaloo 1 and a maximum of 83 m in Exmouth 2 (84–167 m; Chaproniere, 1976). Offshore, it thickens markedly but not consistently until the Rankin Platform area. North and west of the Rankin Platform, it becomes much thinner. This is illustrated by Haycock 1 (1100–?1406 m), Pueblo 1 (1102–1398 m), Brigadier 1 (2040–2187 m) and Delambre 1 (1806–1851 m). The maximum thickness recorded is 415 m in Hilda 1A.

Fossils and age

Onshore, the Trealla Limestone contains a rich fauna of foraminifers, corals, bivalves, gastropods, calcareous worms and calcareous algae. Crespin (1953, 1955) described the microfauna of the Trealla Limestone, and dated the formation as "f" stage Middle Miocene. Chaproniere (1975) detailed the palaeoenvironmental implications of the foraminiferal fauna. Heath and Apthorpe state:

"The unit ranges in age from the basal Middle Miocene to within the Middle Miocene. This age determination is based on the presence of zone N8

planktonic foraminifers at the base of the formation. The upper age limit is based on the last appearance of the *Nephrolepidina howchini* in the area of the Dampier Sub-basin. The last appearance level is undoubtedly facies controlled. However, the best present estimate for this horizon is within the Middle Miocene.

"In the pelagic marls of Brigadier 1 and Delambre 1, samples near the top of the formation contain *Globorotalia peripheroacuta G. peripheroronda, Orbulina suturalis, O. universa* and *Praeorbulina glomerosa circularis*, indicating an age within zone N10 (Middle Miocene)."

Environments of deposition

In the Cape Range–Giralia Range area, the Trealla Limestone was deposited in shallow, agitated water. Largely on faunal evidence, Chaproniere (1975) postulated that the lower, packstone-dominated part of the Trealla Limestone in the Cape Range area formed in water depths of less than 12 m, with normal oceanic salinities and under a sea-grass baffle which may have been protected by a barrier of Pilgramunna Formation, then forming to the west. The grainstones which dominate the upper Trealla Limestone formed in high-energy shallow-water conditions, with winnowing of finer sediment and rounding of coarser sediment by waves. Chaproniere (1975) noted that planktonic foraminifers are absent in the grainstones in Cape Range and suggested metahaline salinities, resulting from restricted salinities because of a barrier of Pilgramunna Formation. He also suggested that sea-grass communities contributed to the sediment, because of the presence of encrusting algae. Lagoonal to lacustrine conditions were locally present in areas close to the Middle Miocene shoreline.

In northern, offshore areas, Heath and Apthorpe (written comm.) state: "A deep-water marine incursion during the basal middle Miocene zone N8 is indicated by the presence of a moderately plantonic-rich interval at or near the base of the Trealla Limestone over much of the southern North West Shelf. Above this, the presence of mostly benthonic foraminifers, including the larger benthonic genera *Nephrolepidina* and *Miogypsina*, suggest deposition in a middle- to inner-shelf environment. Towards the top of the formation the environment of deposition shoals to very shallow shelf conditions which ultimately excluded most of the foraminifers. Algal limestones and recrystallized, evaporite-cemented limestones are common at the top of the formation." Outer-shelf to slope conditions occurred seaward of the Rankin Platform.

LAMONT SANDSTONE

Definition

The Lamont Sandstone was named and defined by Condon and others (1956), and was included in the Cape Range Group by van de Graaff and others (1980). It unconformably overlies older units and can be seen to grade laterally into the lower Trealla Limestone, although the contacts are very poorly exposed. The type section is 2.4 km northeast of Lamont Well, between the Giralia and Marrilla Anticlines.

Lithology

The Lamont Sandstone consists of fine- to medium-grained, locally coarse-grained, generally well-sorted quartz sandstone. It is locally calcareous and commonly intensely silicified. Calcareous portions are very similar to the Pilgramunna Formation.

Distribution and thickness

The unit occurs in the Giralia, Marrilla and Chargoo Anticlines. There is an intensely silicified sandstone less than 2 m thick, on the east side of Hamelin Pool, between Hamelin and Yaringa homesteads, which is identical to the Lamont Sandstone in the Giralia Anticline. It was assigned to the unit by van de Graaff and others (1983). Between No. 9 Bore and Taff's Bore on Yalbalgo, Denman and others (1985) tentatively assigned silicified sandstone of very similar lithology to the Lamont Sandstone. The latter exposures are dissimilar to either the Pindilya Formation or the Merlinleigh Sandstone in surrounding areas. Condon and others (1956) stated that the type section is 3.3 m thick, and this is probably the maximum thickness present anywhere.

Fossils and age

The Lamont Sandstone contains silicified fossil wood in the Chargoo Anticline and at Yaringa Point. The only other fossils known are rare foraminifers which Edgell (1952) considered were Early Miocene. However, field relationships indicate that the Lamont Sandstone is equivalent to the Lower Trealla Limestone, and thus Middle Miocene in age.

Environment of deposition

The Lamont Sandstone contains no sedimentary features which would by themselves be diagnostic of a particular sedimentary environment.

However, the relationship of the unit to the Trealla Limestone, its pattern of distribution, and its generally good sorting suggest that it is a nearshore to shoreline deposit, which developed only in isolated areas where there was terrigenous input and waves could trap and concentrate this terrigenous sediment.

PILGRAMUNNA FORMATION

Definition

The Pilgramunna Formation was named and defined by Condon and others (1955) and included in the "Yardie Group", together with the Vlaming Sandstone. Later, Condon (1968) mistakenly correlated the Vlaming Sandstone with the Exmouth Sandstone, and abandoned the "Yardie Group". However, the Vlaming Sandstone is a valid unit of Miocene age, and van de Graaff and others (1980) included both it and the Pilgramunna Formation in the Cape Range Group.

The Pilgramunna Formation is a quartzose sandy correlative of the Trealla Limestone and, like the latter, rests disconformably on the Tulki Limestone. It is conformably overlain by and (in the upper part) interfingers with the Vlaming Sandstone. The type section (Fig. 112) is on the south bank near the mouth of Yardie Creek.

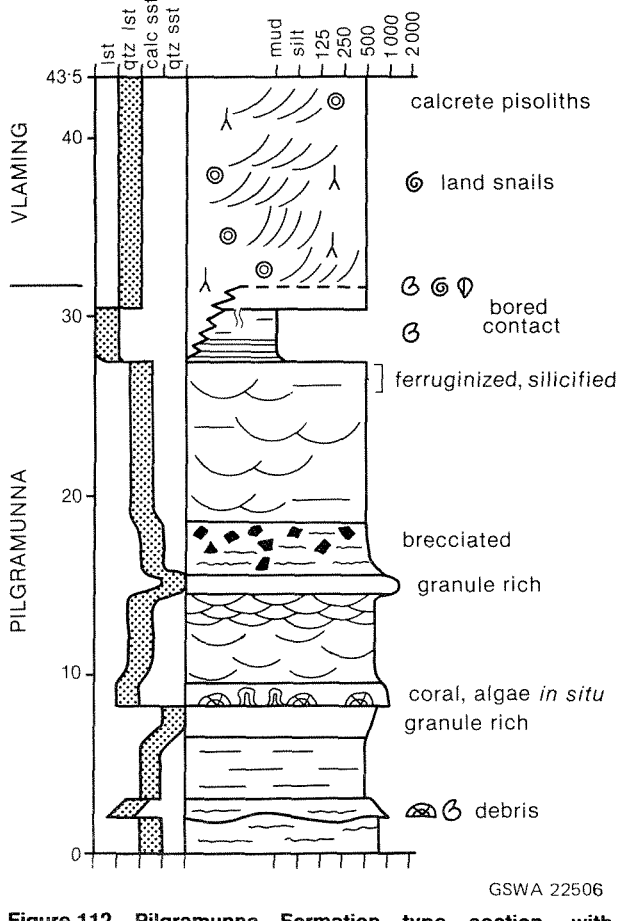


Figure 112. Pilgramunna Formation type section, with portion of Vlaming Sandstone above.

Lithology

The Pilgramunna Formation consists of well-sorted, generally well-rounded, fine- to very coarse-grained quartzose calcarenite (grainstone) to calcareous quartz arenite with interbedded lenses of muddy calcarenite (packstone) and coralgal boundstone (Fig. 113). It is distinguished from the Trealla Limestone by the admixture of silt to granule-size quartz. Because of the quartz content, sedimentary structures weather out clearly in outcrop, and medium- to large-scale cross-bedding is common in clastic portions of the unit. Channel-fill sequences and rare low-angle cross-bedding typical of beach deposits are present, and occur mostly in the upper part of the Pilgramunna Formation, as do rare silicified horizons suggestive of soil deposits. However, heavy-mineral accumulations are not known. In the type section, calcilutite lenses occur at the top of the Pilgramunna Formation, overlain by eolian Vlaming Sandstone, and are interpreted as discontinuous lagoonal deposits. Storm-beach deposits occur locally (Fig. 114).

Distribution and thickness

Exposure of the Pilgramunna Formation is limited to the western flank of Cape Range where the thickness of the formation varies between 20 and 30 m. In the subsurface, the Pilgramunna Formation has only been recognized in West Muiron 1 and 2 where it is 92 and 96 m thick, respectively. It was not differentiated in Muiron 1, but the interval between 305 and 341 m may be Pilgramunna Formation, at least in part. The Bare Formation is a lateral equivalent of the Pilgramunna Formation which occurs northeast from Tryal Rocks 1.

Fossils and age

The Pilgramunna Formation contains a very meagre fauna, much of which appears to be reworked from the Trealla Limestone (Chaproniere, 1975). The fauna includes corals, calcareous algae and worms, bivalves, gastropods, foraminifers (listed by Crespin, 1953, 1955) and the nautiloid *Aturia* cf. *australis* (A. E. Cockbain, written comm). Quilty (1974) and Chaproniere (1975) regarded the Pilgramunna Formation as Middle Miocene (N9) in age.

Figure 113. Pilgramunna Formation, approximately 1 km southwest of Vlaming Head lighthouse. Cross-bedded quartzose calcarenite with large ?fallen block of coralgal reef facies (arrowed).

Environment of deposition

The Pilgramunna Formation was deposited in shallow, high-energy conditions as a long, north-south oriented shoaling sand bar or sand spit. The source of the sand probably was the ancestral Lyndon River, because if either the ancestral Minilya or Gascoyne Rivers were the sources for the Pilgramunna Formation, siliciclastic facies should be present in the Trealla Limestone in the anticlines surrounding Lake MacLeod. The environment shallowed during deposition, and emergence occurred intermittently during the deposition of at least the upper part of the Pilgramunna Formation. At this time, it formed a significant barrier which protected areas to the east and may have begun to inhibit water circulation there. This ushered in the metahaline conditions which Chapronierc (1975) suggested prevailed during deposition of the upper, grainstone-dominted Trealla Limestone in Cape Range.

VLAMING SANDSTONE

Definition

The name Vlaming Sandstone was introduced by Condon and others (1955) for the unit overlying the Pilgramunna Formation. Condon (1968) considered the unit was equivalent to, and a junior synonym of, the Exmouth Sandstone. Following detailed mapping, van de Graaff and others (1976) disproved this and concluded that the Vlaming Sandstone was a valid unit. The type section is 1.6 km south-southeast of Tulki Well, and is about 38 m thick, the basal 3 to 4 m being transitional with the underlying Pilgramunna Formation. It is overlain with angular unconformity by the Exmouth Sandstone or younger eolian sediments.

Lithology

The Vlaming Sandstone consists of well-sorted, medium-grained quartzose calcarenite (Fig. 112). Sets of large-scale, steep cross-beds up

GSWA 22508

Figure 114. Pilgrammunna Formation, east of Tantabiddi Well. Breccia separating Pilgramunna Formation quartzose calcarenite from Vlaming Sandstone. Presumably formed as storm-beach deposit after brief hiatus.

to 12 m high are locally visible, and are probably common. They are separated in places by calcreted soil units containing scattered land snails. The sandstone is usually gradational from the Pilgramunna Formation.

Distribution and thickness

The type section of the Vlaming Sandstone is 38 m thick, and the thickest section measured during mapping was 65 m. It has a linear distribution along the west flank of Cape Range, closely associated with the distribution of the Pilgramunna Formation. The stratigraphic relationships of the unit were described in detail by van de Graaff and others (1976) and are shown in Figure 115.

Fossils and age

The Vlaming Sandstone has no fossils which give a precise age. Land snails occur as calcrete-pisolith cores near Vlaming Head. On stratigraphic position and field relationships it is likely to be partly equivalent to the Pilgramunna Formation and Trealla Limestone (in particular the upper part), and is therefore of Middle to Late Miocene age.

Environment of deposition

The Vlaming Sandstone is an eolian deposit which formed behind, and on, the beach and littoral deposits of the Pilgramunna Formation. In places it overlies lagoonal to near-shore facies of the Pilgramunna Formation and locally it interfingers with the latter, as at 21°56′30″S, 114°00′45″E. The deposition of the Vlaming Sandstone served to fully bar the area to the east and restrict its water circulation to a northerly (and possibly southerly) exit, thus producing the metahaline conditions which Chaproniere (1975) suggested for deposition of the upper Trealla Limestone.

BARE FORMATION

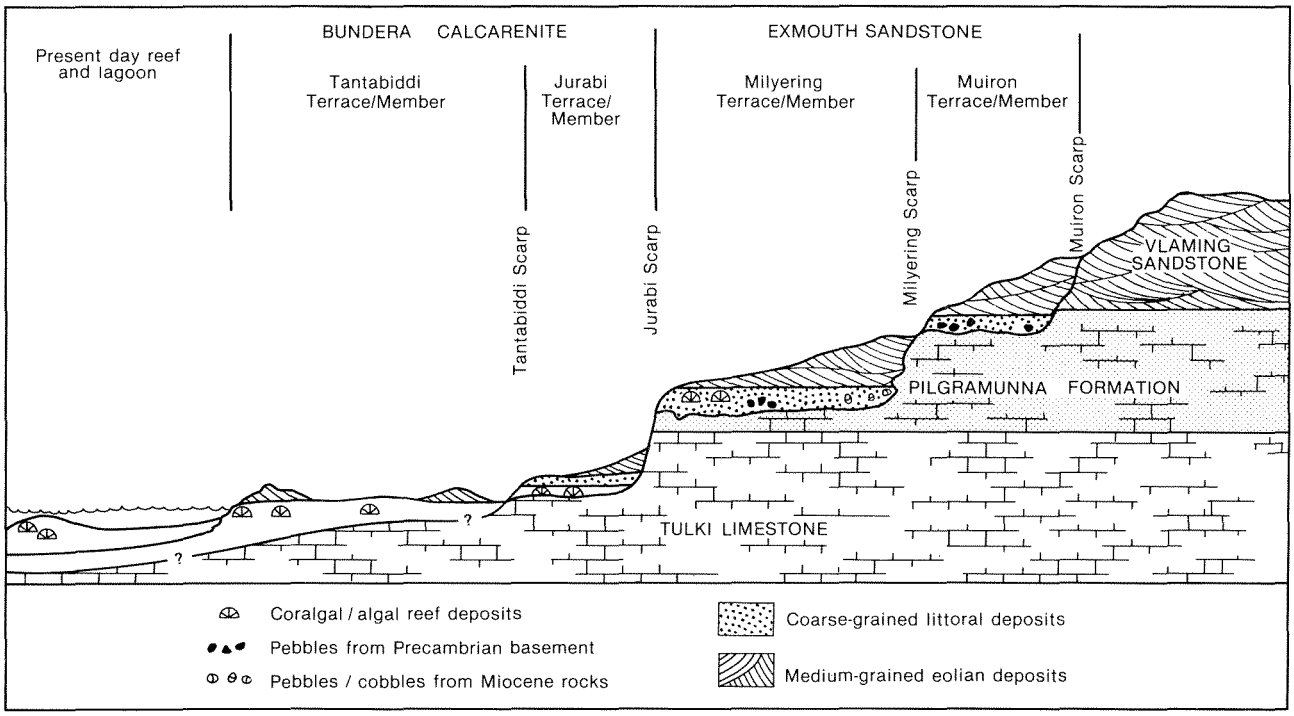
(R. S. Heath and M. S. Apthorpe)

Definition

The Bare Formation is a mixed sandstone and carbonate sequence which conformably overlies the Trealla Limestone in the Rankin Platform area, the boundary between the two being gradational in some wells. The Bare Formation is overlain by the Delambre Formation, probably disconformably, as sand from the Bare Formation is often reworked into the base of the overlying unit. The upper boundary is marked by sonic and gamma-ray log breaks, reflecting a change from the variable lithology of the Bare Formation to the more uniform and finer grained characteristics of the calcareous Delambre Formation. The type section is in Goodwyn 6 between 712 and 1120 m (Fig. 116).

Lithology

The Bare Formation consists of interbedded sandstone and calcarenite with a basal dolomite. The sandstone is colourless to white and yellowish brown, moderately to well sorted, dominantly medium grained (but ranging from very fine to coarse grained) and unconsolidated to well cemented. Grains are subrounded to well rounded and generally frosted. The calcarenite is white to grey, dominantly fine grained but ranging from very fine to coarse grained, moderately hard and contains up to 10% skeletal fragments, mostly recrystallized beyond identification. It locally grades into calcisiltite. The dolomite occurs be-



GSWA 22509

Figure 115. Stratigraphic relationships of Miocene and Pliocene/Pleistocene units on west side of Cape Range. Note that recognition of specific units is dependent largely on elevation and the recognition of abutment unconformities.

tween 1050 and 1120 m in the type section and is white to yellowish grey with trace amounts of quartz grains.

The lithology, inferred depositional environments, and stratigraphic relationships of the Bare Formation are similar to the Pilgramunna Formation in the Cape Range area, and the two units are probably lateral equivalents. The sediments here placed in the Bare Formation are not included in the Pilgramunna Formation because of the distance between the two areas, and the significantly greater thickness of the Bare Formation.

Distribution and thickness

The Bare Formation is present over the Rankin Platform and in the Angel area but does not extend as far north and west as Delambre 1 and Brigadier 1. The distribution of the formation is unknown to the southeast of a line running through Angel 3, Walcott 1, and Dampier 1, as wells inshore from these have no samples recovered from above the 20 inch casing point. The sandy calcarenite and calcareous sandstone noted in Tryal Rocks 1 by Quilty (1974) is here assigned to the Bare Formation.

To the northeast of the Dampier Sub-basin (*i.e.* Sable 1, Ronsard 1 and wells further east) the quartz sandstone of the Bare Formation gives way to interbedded limestone and dolomite, and the formation is difficult to distinguish from adjacent units. Again, inshore well control is lacking.

Some thicknesses of the Bare Formation are as follows: Fisher 1, 945–1160 m; North Rankin 5, 560–approximately 1050 m; Walcott 1, above 421–?749 m (top not sampled); Lambert 1, above 450–1155 m (top not sampled); Angel 3, 396–807 m (not sampled); Ronsard 1, 933–1218 m.

Fossils and age

The Bare Formation is barren except for very sparse shallow-water benthonic foraminifers, which are not age diagnostic.

The lithological and apparent environmental gradation, from the Trealla Limestone to the Bare Formation, suggests that the latter is Middle Miocene. The relatively abrupt boundary with the overlying Delambre Formation, the base of which is latest Late Miocene (or "undifferentiated Late Miocene to Early Pliocene" in some wells) indicates that deposition of the Bare Formation ceased no later than the Late Miocene.

Environment of deposition

The intercalation of dolomites and sandstones in the Bare Formation, in combination with the virtual absence of fauna, suggests that it was deposited in a coastal setting. The maturity of the sandstone and frosting of the grains suggest that sandstone intervals formed in a nearshore to beach

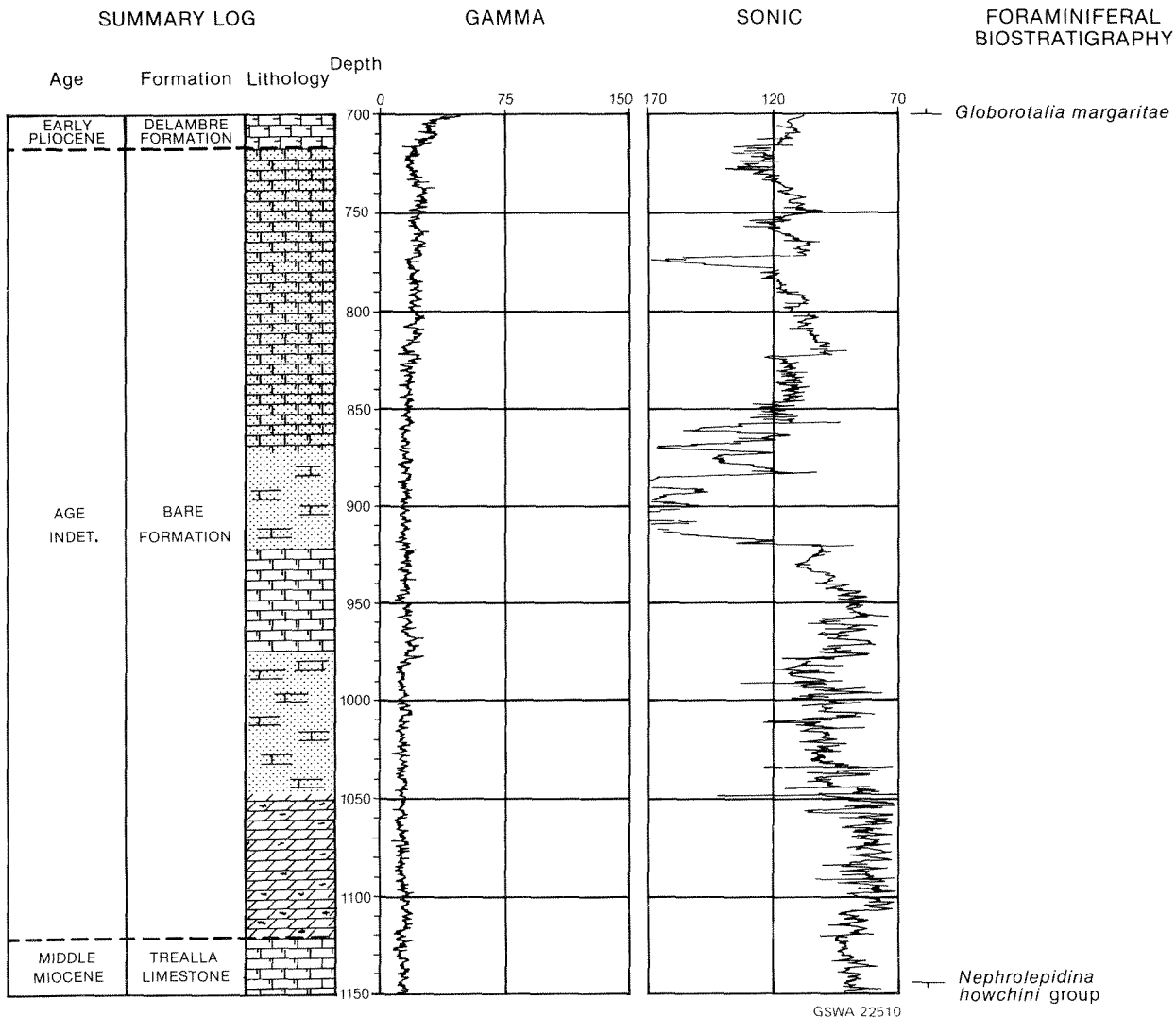


Figure 116. Bare Formation type section, Goodwyn 6.

or dune environment, and that the dolomite intervals formed in protected highly saline lagoonal to intertidal areas.

UNGROUPED UNITS

DELAMBRE FORMATION

(R. S. Heath and M. C. Apthorpe)

Definition

The Delambre Formation (Heath and Apthorpe, 1984) is a fine-grained calcareous sequence which occurs along the Rankin Platform and in areas to the north and west. It overlies the Bare Formation, with a sharp contact. The contact and the transgressive nature of the Delambre Formation, suggest a disconformable contact. West of the Rankin Platform in Brigadier 1, the base of the Delambre Formation is Early Pliocene (zone N18) and it rests disconformably on Middle Miocene (zone N10) Trealla Limestone. In Delambre 1, the oldest sampled part of the formation is late Middle Miocene (N14) but the contact with the underlying Trealla Limestone was not sampled, so its nature is not clear.

The type section is in Fisher 1 between 405 and 945 m (Fig. 117A). The top of the Delambre Formation is probably the sea floor. There is no information on the interval above 405 m in Fisher 1, or above about 300 m in most other wells. A reference section for the upper part of the formation is given by a composite of three core holes and push cores drilled from, or near, the North Rankin "A" production platform. Push cores BH2A and BH2B were drilled in 1978, 77 and 34 metres, respectively, to the west of the North Rankin "A" Platform. They penetrated from the sea floor to 125.8 m depth. North Rankin "A" conductor core CE1 intersected a sequence from 112 to 235 m below sea floor. As a composite, these cores intersect the Holocene, Pleistocene and

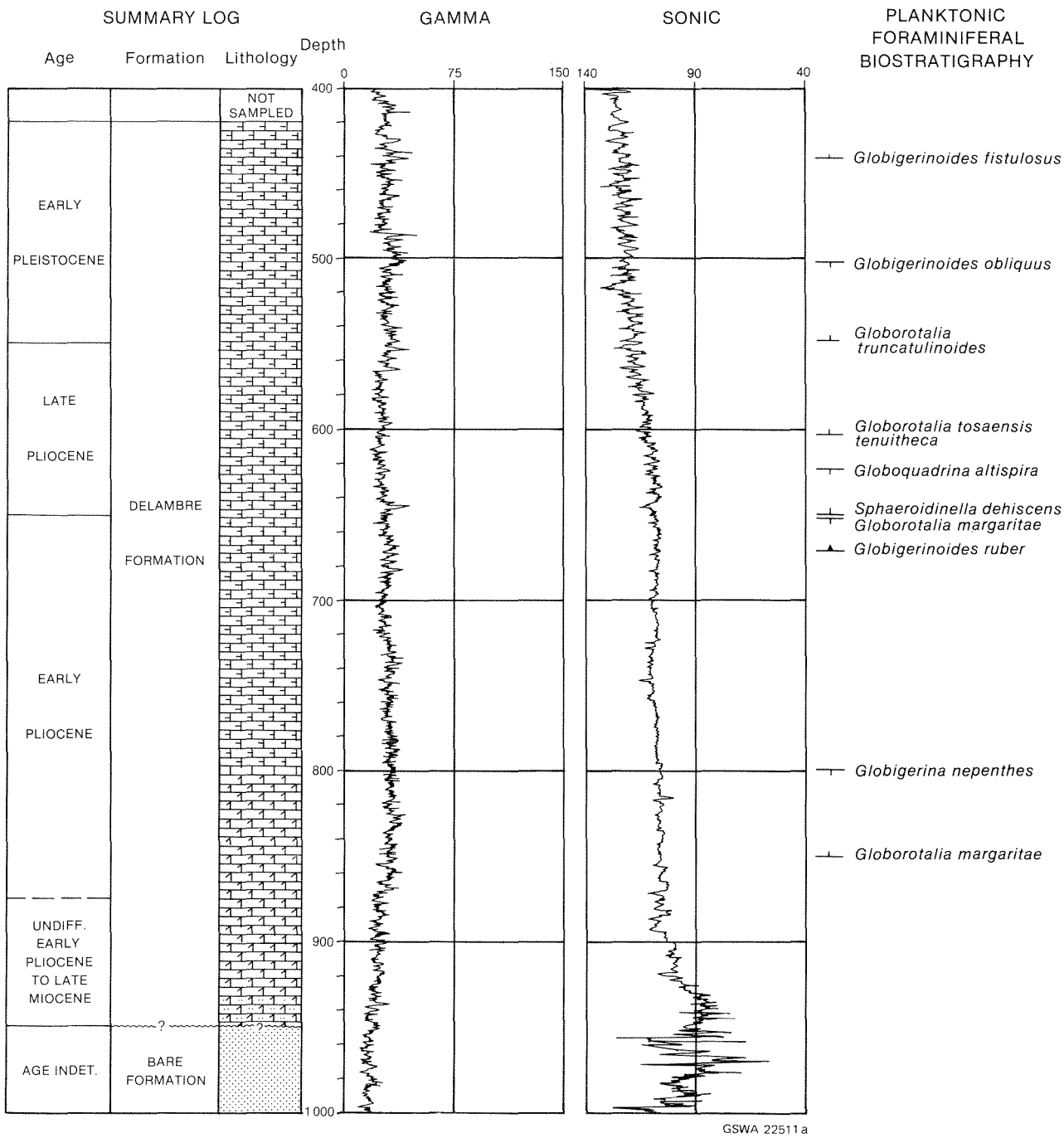
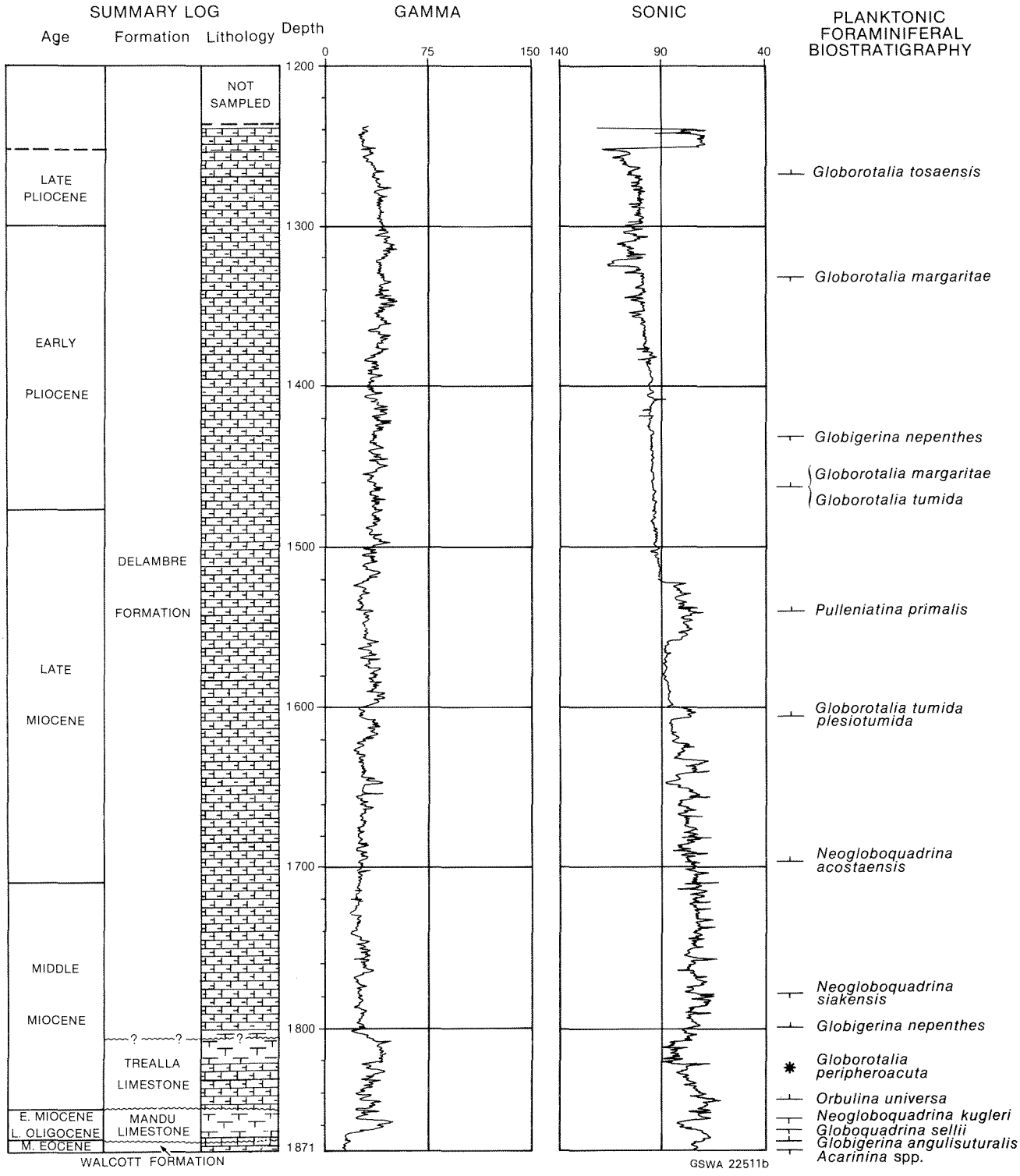


Figure 117. A. Delambre Formation type section, Fisher 1.



B. Delambre Formation reference section, Delambre 1.

some of the Pliocene of the Delambre Formation. They suggest a possible subdivision of the formation into two members in this area.

Lithology

The Delambre Formation consists of calcilutite, grading in the lower third of the formation to silty calcilutite and calcisiltite. The calcilutite is greenish grey to grey, soft, and contains up to 10% skeletal debris (mostly foraminifers with minor bryozoans, algae, ostracods, and shell fragments), quartz silt, and traces of glauconite. The calcisiltite is buff grey to greenish grey, moderately soft and contains 20 to 40% quartz silt, up to 5% glauconite, and up to 10% skeletal debris as above. In several sections there is minor sand at the base of the formation. This is probably a reworked lag from the top of the Bare Formation, rather than a gradational contact.

The extreme softness of most of the unit leads to much washing out of the fine-carbonate mud during drilling. This concentrates skeletal fragments and coarser grains in ditch-cutting samples. The actual lithology, soft calcilutite, is only shown by sidewall cores.

In the North Rankin area, the Delambre Formation appears to consist of two members. Between the sea floor and 111.5 m, the formation is dominantly a soft, grey calcilutite containing abundant biogenic detritus and thin beds of more indurated, cemented, bioclastic calcisiltite to calcarenite. The lower member, between 111.5 and 235 m is a grey calcarenite, ranging from fine to coarse grained but dominantly fine grained below 190 m. Biogenic particles include shell fragments, foraminifers and algae. The lower member ranges from well to poorly cemented, and has so far only been encountered in the North Rankin area.

Distribution and thickness

The sampled thickness of the type section in Fisher 1 is 540 m, while the reference section at North Rankin A is more than 235 m thick.

The Delambre Formation is well developed along the Rankin Platform, for example in Goodwyn 6 where it extends from above 500 m to 710 m. It extends northeast at least as far as Cossigny No. 1, and is greater than 1340 m thick in Brigadier 1. On seismic sections close to the present edge of the continental shelf, the formation is visible as a series of gently prograding reflectors.

Inshore from the Rankin Platform, the formation lies above the level of first sample returns in offshore wells.

Fossils and age

The Delambre Formation is late Middle Miocene to Holocene in age. The type section ranges from undifferentiated earliest Pliocene to latest Miocene at the base, through to the Early Pleistocene (Fig. 117A).

In most wells adjacent to the Rankin Platform the same time span is seen, although sampling of the top of the formation is always incomplete. In Delambre 1, the formation appears to extend down in a complete sequence into the late Middle Miocene (Zone N14) based on the overlapping ranges of *Globigerina nepenthes* and *Neogloboquadrina siakensis* (see Fig. 117B). The lithological relationships of this, the oldest part of the Delambre Formation, with other formations require further elucidation from future drilling. The base of the unit in Delambre 1 is sampled insufficiently to resolve the correlation problems of whether it is a time equivalent of the Bare Formation.

In the three North Rankin Platform bores, the age of the upper member is Pleistocene (Zone N22), with the topmost sample being dated as latest Pleistocene to Holocene, based on the presence of *Emiliania huxleyi* (Paltech, 1979). The top of the lower calcarenite member cannot be dated, because planktonic foraminifers are absent. The lowest samples within the calcarenite are of Early Pliocene (Zone N19) age. The conductor corehole CE1, has been examined only briefly, and requires detailed study.

Environment of deposition

Along the Rankin Platform the foraminiferal assemblages record a rapid transgressive episode after deposition of the Bare Formation. Inner-shelf, planktonic-poor assemblages were rapidly replaced by planktonic-dominated, middle-shelf assemblages. In Fisher 1, deposition occurred in approximately 100 m water depth throughout the Pliocene. A rapid increase in sedimentation rate in the latest Pleistocene to Holocene is evident in several wells, including Lowendal 1, Haycock 1, and Parker 1.

In the North Rankin Platform bores, there is evidence of marked shallowing (to inner-shelf depths) at the top of the lower (calcarenite) member, followed by renewed deepening to at least

middle-shelf depths in the upper member. The complex Pleistocene sequence, in particular, requires detailed study. In wells further offshore such as Brigadier 1 and Delambre 1, deposition occurred in much greater water depths. In Brigadier 1, the Lower Pliocene base of the Delambre Formation was deposited within the water depth range 700–1300 m, on the continental slope. Rapid deposition led to a water depth of 200–300 m before the end of the Pliocene.

PINDILYA FORMATION

Definition

The Pindilya Formation was named and defined by Konecki, Condon, Dickins and Quinlan (*in* McWhae and others, 1958) but van de Graaff and others (1977) discovered that the designated type section consisted of Moogooloo Sandstone. Since the Pindilya Formation is a valid unit, a new type section was chosen on the western side of a low mesa between Salt Well and Swelt Bore on Curbur Station. The position of this section is clearly shown by Williams, I. R., and others (1983). The Pindilya Formation is conconformable on older rocks, with the unconformity commonly marked by deep solution pipes which formed during lateritization and silcretization. The unit itself is intensely silcreted, and difficult to distinguish from silcreted older units and residual soil. It is a thin sandy and conglomeratic unit which originated partly through alluvial and partly through residual weathering processes.

Lithology

The Pindilya Formation consists of sandstone and granule to pebble conglomerate with lesser siltstone. The type section consists of 1.7 m of indistinctly bedded, well-sorted, quartz-pebble conglomerate with pebbles ranging in size from 2 mm to 3 cm, grading up into 1.1 m of more distinctly bedded, very coarse-grained quartz sandstone to granule conglomerate. The section is intensely silcreted (van de Graaff and others, 1977). In most outcrops sorting is poor, and because the unit is commonly silcreted it is difficult to distinguish from silcreted residual sediment. In the area between Yaringa 1 and Kopke Point typical poorly sorted, flat-bedded, silcreted Pindilya Formation, showing laminar and pisolitic soil structures at the top (near Yaringa 1), appears to grade westwards through a series of north-facing breakaways to moderately sorted and rounded, medium-grained typical Lamont Sandstone (near Kopke Point).

Distribution and thickness

The Pindilya Formation occurs as caps on some mesas in the Byro and southern Bidgemia Sub-basins and extends west beneath the sand cover of the Victoria Plateau. Sediments of similar lithology are present further west in the same morphostratigraphic position: on the western side of the Victoria Plateau in the breakaways north of Mount Curious near the Murchison River gorge; in the gorge and bed of the Wooramel River where it incises the Victoria Plateau; and in the breakaways through which the Northwest Coastal Highway passes near Yaringa 1. The latter exposures were shown by van de Graaff and others (1983) as Lamont Sandstone because of apparent lateral continuity of outcrop with Lamont Sandstone to the west. The Victoria Plateau Sandstone of the Perth Basin (Playford and others, 1976) occurs in a similar morphostratigraphic setting, and correlates with the Pindilya Formation.

The new type section of the Pindilya Formation is 2.8 m thick, and elsewhere in the Byro and Bidgemia Sub-basins the unit is less than 6 m thick, of which a significant amount is within karst-type solution pipes. Only a veneer of weathered-out pebbles and cobbles is commonly present. Beneath the Victoria Plateau, the Pindilya Formation may be 10-15 m thick in places.

The Pindilya Formation is a widespread unit which was deposited on an ?Early Tertiary erosion surface, and underwent some erosion and dissection before intense lateritization and silcretization took place. The duricrust masks underlying lithologies with a uniform photo pattern, and for this reason it is difficult, if not impossible, to determine (by photo interpretation) to what extent isolated hill tops have been stripped of Pindilya Formation.

Fossils and age

The only fossils found *in situ* in the Pindilya Formation are root casts. Konecki and others (1958, p. 56) reported poorly preserved fossils found near, but not in, exposures of Pindilya Formation and in similar chalcedonic preservation to fossils from the Eocene Merlinleigh Sandstone, and they tentatively correlated the two units. Later investigation by van de Graaff and others (1977) did not clarify whether or not these fossils were actually from the Pindilya Formation, but the probable non-marine nature of the unit renders it unlikely. The apparent lateral transistion from the Pindilya Formation to the Lamont Sandstone in the Yaringa area suggests that a Miocene age may be more tenable for the Pindilya Formation.

Environment and deposition

The poor sorting and widespread but thin distribution of the Pindilya Formation suggests that it was deposited in a fluvial environment largely by sheet-flood processes. In many areas it overlies fine-grained sediments which could not supply the necessary sand- to pebble-sized material, and hence is probably of fluvial origin, but elsewhere much of the unit may be residual, without significant transport of sediments.

QUATERNARY: CAPE RANGE AREA

Differentiation of the Exmouth Sandstone and Bundera Calcarenite, the two Quaternary formations in the Cape Range area, is based primarily on the more dissected outcrop and greater quartz content of the former. Both are relatively thin units in outcrop, but in subcrop they thicken dramatically in some areas. Muiron 1 penetrated 336 m of undifferentiated Bundera Calcarenite and Exmouth Sandstone.

EXMOUTH SANDSTONE

The Exmouth Sandstone (Exmouth Formation of Craig, 1950; amended by Condon and others, 1953) consists of well-sorted, fine- to medium-grained, quartzose calcarenite, with large-scale cross-bedding and occasional calcrete-soil intercalations. The type section is southwest of Learmonth airfield and is 8.5 m thick. The lowermost 3.5 m of the 12 m measured by Condon and others (1953) is actually weathered Trealla Limestone. The Exmouth Sandstone unconformably overlies the Miocene Cape Range Group and is in turn unconformably overlain by the Bundera Calcarenite or younger units.

Muiron and Milyering Members

On the west side of Cape Range, the Exmouth Sandstone was divided into the older Muiron Member and the younger Milyering Member by van de Graaff and others (1976). The relationships of these units are shown in Figure 115. The two members are lithologically similar; both consist of coarse-grained to pebbly, quartzose calcarenite at the base, grading up into a few tens of metres of well-sorted medium-grained quartzose calcarenite with steep, large-scale cross-bedding. In the lower part of the Milyering Member the locally irregular unconformity is in places overlain by coralgal boundstone deposits. In both members the sequence from coarse to finer grained sediments is interpreted as a transition from (sub)littoral to eolian deposits. Pebbles of banded iron-formation, quartz-tourmaline rock, and other Precambrian rock types found in the coarse-grained lower parts of the members indicate that the Ashburton river was one source of supply, as it carries an identical assemblage.

These two lithologically similar members are differentiated because they occur on two different emerged shoreline terraces (van de Graaff and others, 1976). In previous mapping by Condon and others (1953, 1955) they were mistaken for the lithologically similar Pilgramunna Formation, possibly because they have a similar distribution along the west side of Cape Range.

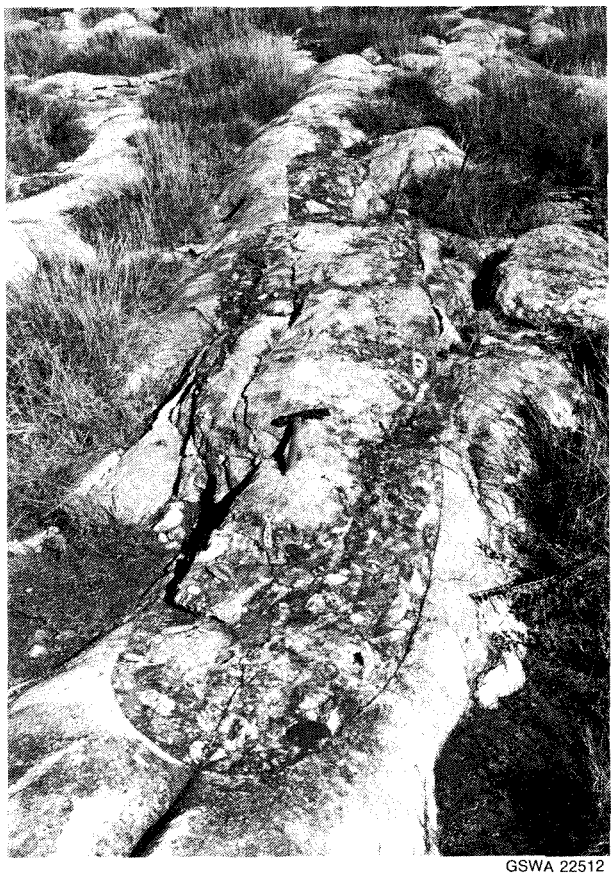
Crespin (1953, 1955) considered the Exmouth Sandstone to be of Pleistocene age on the basis of foraminifers. Physiographic evidence supports this, but attempts to radiometrically date corals from the unit have been unsuccessful. The Exmouth Sandstone probably correlates in large part with the Peron Sandstone of the Shark Bay area, but a correlation with the lower part of the Tamala Limestone cannot be dismissed.

BUNDERA CALCARENITE

The Bundera Calcarenite (Bundera Limestone, Condon and others, 1953; amended by Condon, 1954) consists of calcarenite to calcirudite with extensive coralgal reef deposits. The type locality is in a large sinkhole near Bundera Well, where 6.0 m of calcarenite and calcirudite is exposed. The formation underlies most of the coastal plains on the Cape Range peninsula, and forms the core of most, if not all, of the islands except Barrow Island. On the Cape Range peninsula, the formation unconformably overlies or abuts the Exmouth Sandstone or the Cape Range Group.

Jurabi and Tintabiddi Members

Van de Graaff and others (1976) recognized two members in the Bundera Calcarenite, the older Jurabi Member and the younger Tantabiddi Member, which are lithologically similar but physiographically distinct because they occur on separate emerged shoreline terraces (Fig. 115). The thickness of both units probably does not exceed about 20 m onshore. The Jurabi Member (Fig. 118) differs from the Tantabiddi Member in containing more coralgal reef deposits and less eolian calcarenite. Two units can be recognized within the Bundera Calcarenite on the flanks of the anticlines surrouding Lake MacLeod, but these have not been formally assigned to the named members because of uncertainties in correlation.



GSWA 22512

Figure 118. Jurabi Terrace, showing scour cut in Tulki Limestone infilled with Jurabi Member conglomerate and algal deposits.

Shallow-marine to littoral deposits within the Bundera Calcarenite are restricted to the flanks of anticlines and islands, but eolian deposits are far more widespread and infill the areas between anticlines as well as forming some of the islands (*e.g.* North Murion Island). Swampy deposits may occur in Lake MacLeod (Fig. 119).

Mowbowra Conglomerate Member

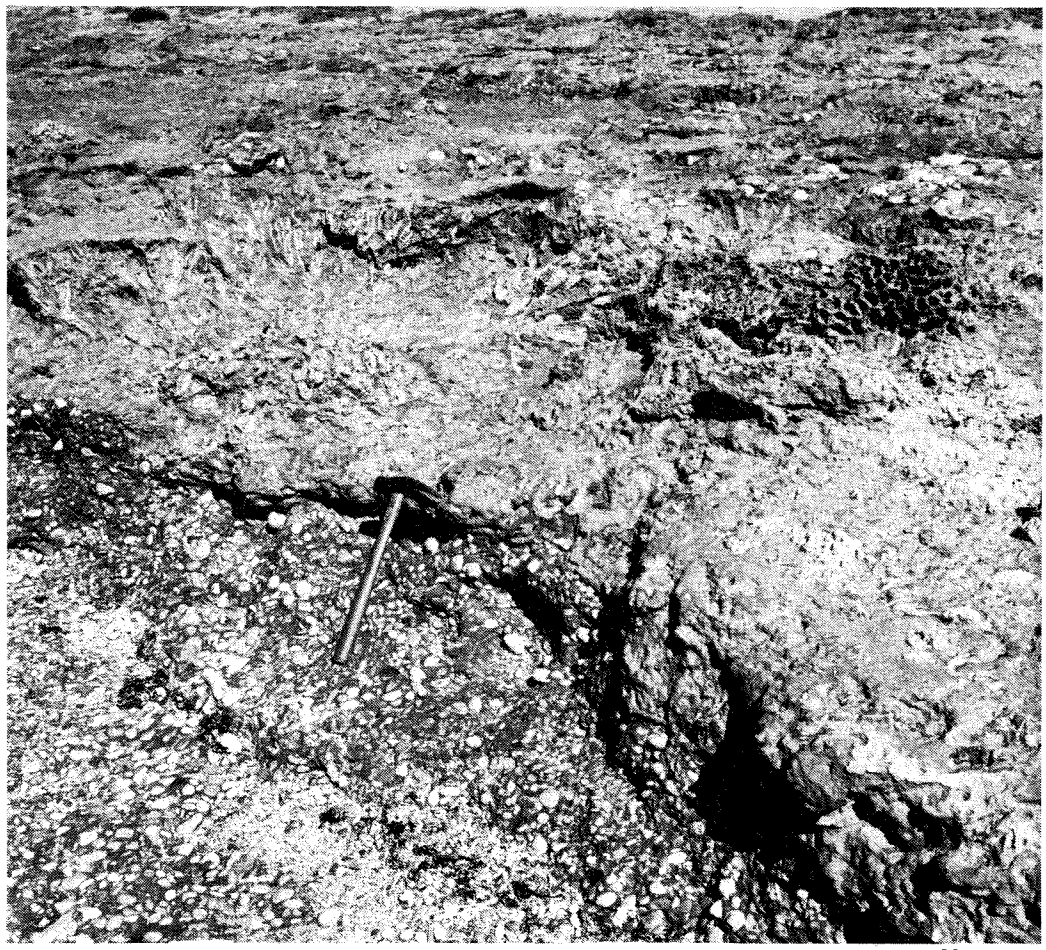
This member ("Mowbowra Conglomerate" of Condon and others, 1953; amended by van de Graaff and others, 1980) consists of limestone-pebble conglomerate, well-sorted calcarenite and minor coralgal reef deposits (Fig. 120). The type section of the unit is at the mouth of Mowbowra Creek and is about 6 m thick. Here, the member is interpreted as a foreshore to beach conglomerate interfingering with a coralgal reef. About 250 m to the west, the conglomerate forms elevated ridges which are interpreted as storm-beach deposits that overlie poorly sorted, calcreted alluvial sediments. In this interpretation the presence of marine fossils as clasts in the conglomerate is considered to indicate supply of sediment by the sea. Only the *in situ* coralgal reef and the well-sorted, calcarenitic beach deposits provide evidence of a relative sea-level stand.

On the west side of the peninsula similar gravel deposits are presently forming at the mouth of Mandu Mandu Creek, and where that creek and Yardie Creek emerge from the range, lenses of identical conglomerate occur in the Jurabi Member.

The Bundera Calcarenite contains a fauna of modern aspect. Corals from the Tantabiddi Member in Cape Range, from outcrops at Cape Cuvier and from the anticlines surrounding Lake MacLeod, have been dated radiometrically at 123 000 and 128 000 years, respectively (Veeh and others, 1979). The eolian deposits of the Bundera Calcarenite correlate with the Tamala Limestone, and the marine parts probably correlate with the Bibra Limestone and possibly the Dampier Limestone.

GSWA 22513

Figure 119. Bundera Calcarenite, west side of Lake MacLeod, with preserved leaf impressions. Plants presumably grew in a coastal swamp. Scale bar is 10 cm.



GSWA 22514

Figure 120. Mowbowra Conglomerate Member, mouth of Mowbowra Creek. Conglomerate overlain by *in situ* coral reef.

QUATERNARY: SHARK BAY AREA

The Quaternary sediments and environments of the Shark Bay area were described in great detail by Logan, Davies and others (1970) and Logan, Read and others (1974), with a summary by Logan, Brown and Quilty (1976). Van de Graaff and others (1983) and Butcher and others (1983) provided stratigraphically oriented summaries.

PERON SANDSTONE

The Peron Sandstone (Logan, 1968) is a generally structureless, poorly consolidated, quartz sandstone; it is red in outcrop and red, yellow, or red-brown in subcrop (Logan, Read and Davies, 1970), It overlies Cretaceous and Tertiary sediments unconformably and is overlain or onlapped by the Tamala Limestone, as shown by Logan, Read and Davies (1970, Fig. 4). The maximum thickness of about 100 m is on the Peron Peninsula. A calcrete zone at the top of the Peron Sandstone has partially preserved the original morphology: a series of large interlinked transverse and longitudinal dunes. The lack of marine fossils and the presence of soil profiles, containing insect pupal cases and rare land snails, confirm an eolian origin.

The Peron Sandstone is thought to be at least 250 000 years old, and could well extend into the Pliocene (Logan, Read and Davies, 1970), It probably correlates with older eolianites on the eastern side of the Victorian Plateau (van de Graaff and others, 1983; Hocking and others, 1983) and may correlate with the Exmouth Sandstone.

TAMALA LIMESTONE

The Tamala Limestone ("Tamala Eolianite" of Logan, 1968 and Logan, Read and Davies, 1970; amended by Playford and others, 1976) and its correlatives extend around virtually all the Western Australian coastline, making it possibly the most widely distributed unit in Western Australia. Named correlatives are the Bundera

Calcarenite in the northern Carnarvon Basin and the Bossut Formation in the Canning Basin (Towner and Gibson, 1983). The Tamala Limestone itself is recognized in the southern Carnarvon and Perth Basins. It consists of consolidated to unconsolidated, medium- to coarse-grained, variably quartzose calcarenite. Large-scale eolian cross-stratification and fossil soil horizons are common. Insect pupal cases and land snails are also present (Kendrick, 1978). The formation forms the Zuytdorp Cliffs and the type section, 251 m thick, is near the highest point, north of Womerangee Hill (Fig. 10). About 25 m of Tamala Limestone is present between the top of the type section and the crest of Womerangee Hill, and the base of the unit is an unknown depth below sea level, which suggests that it is at least 300 m thick in this area.

Stratigraphic relationships indicate that the Tamala Limestone is of Pleistocene age, but its exact age is indefinite. The unit formed as coastal sand-dunes during glacially caused Pleistocene low sea-level stands. At these times, wide expanses of unconsolidated marine-carbonate sediments were exposed, some of which would have been reworked by wind to form the thick, extensive dune belt of the Tamala Limestone. The thickness of the Tamala Limestone along the Zuytdorp Cliffs and the presence of marine intercalations suggest that deposition spread over more than one low sea-level stand.

DAMPIER LIMESTONE

The Dampier Limestone ("Dampier Formation" of Logan, Read and Davies, 1970; amended by van de Graaff and others (1983) is the oldest marine-dominated unit recognized in the Shark Bay area and has its type section in Broadhurst Bight on the Peron Peninsula. The formation consists of shelly, foraminiferal and bioclastic calcirudite and calcarenite, commonly a coquinite. A coral-reef facies is present along the eastern margin of Dirk Hartog Island (Logan, Read and Davies, 1970). The upper surface of the Dampier Limestone is commonly intensely calcreted, with solution pipes locally developed. The degree of calcretization commonly distinguishes the Dampier Limestone from the Bibra Limestone where both are present in an outcrop.

The Dampier Limestone is mostly between 1 and 3 m thick, with a maximum of 4.5 m (Butcher and others, 1983), and outcrops of marine deposits are found at elevations ranging from below sea level to about 2.5 m above sea level. Beach-ridge and storm deposits are somewhat thicker, and reach elevations of 11 m above sea level (Logan, Read and Davies, 1970).

The Dampier Limestone was deposited in shallow-marine (less than 3 m) tidal-channel, tidal-flat, storm-beach, and beach-ridge environments, within interdune depressions of the Peron Sandstone and Tamala Limestone landscape. This landscape closely resembled the present-day landscape and was partially flooded during the Dampier marine phase (Logan, Read and Davies, 1970) of the "middle" Pleistocene, not less than about 240 000 years B.P. Normal oceanic salinities prevailed except in restricted southern inlets, which were metahaline (Logan, Read and Davies, 1970).

Carbla Oolite Member

This member ("Carbla Oolite" of Logan, 1968 and Logan, Read and Davies 1970; amended by van de Graaff and others, 1983) is a well-sorted largely unfossiliferous ooid grainstone, with a discontinuous basal fossiliferous conglomerate (the "Gladstone Member" of Logan, 1968). The unit forms distinctive low ridges along the eastern side of Hamelin Pool. A small outcrop is present southeast of Point Petit Bore on the western margin of Hamelin Pool, and it subcrops beneath the Nilemah, Hutchison and Gladstone embayments (Logan, Read and Davies, 1970). The type section is at Goat Point, on the eastern side of Hamelin Pool.

Oysters occurring *in situ* in the basal conglomerate show that it was deposited subaqueously. Logan, Read and Davies (1970) considered that the presence of *in situ* fossils at various levels within the overlying oolitic facies indicated that it was also deposited subaqueously, as shallow subtidal to intertidal shoals. However, van de Graaff and others (1983) noted the resemblance of the oolitic facies to oolitic dunes presently forming north of Carbla Point and south of Kopke Point, and suggested a beach-ridge/coastal-dune environment. This environment implies a lower sea level than suggested by Logan, Read and Davies (1970), and seems more probable for the more inland, upper parts of the Carbla Oolite Member, where there is no apparent control of the unit by basement topography.

DEPUCH FORMATION

The Depuch Formation (Logan, Read and Davies, 1970) is a unit of well-indurated, red-brown calcarenite and calcirudite which is present

in thin, narrow strips around the margins of promontories in Edel Land. It contains fossil pupal cases (Logan, Read and Davies, 1970) and it formed by the erosion and colluvial reworking of older Pleistocene units in low areas, after the Dampier marine phase.

BIBRA LIMESTONE

The Bibra Limestone ("Bibra Formation" of Logan, Read and Davies, 1970; amended by van de Graaff and others, 1983) formed during the Bibra marine phase of Logan, Read and Davies (1970). It consists of bivalve coquinite, skeletal calcirudite and calcarenite, and coral biostromal limestone. It is commonly calcreted, but to a lesser degree than the Dampier Formation. The morphology, lithology, and fossil assemblages of the Bibra Limestone allow recognition of beach-ridge deposits, tidal-flat deposits and coral reefs (in the Gladstone embayment and at Crayfish Bay). The fossil assemblage indicates that normal oceanic salinities prevailed during deposition (Logan, Read and Davies, 1970).

The Bibra Limestone is widely exposed in the tidal flats around Shark Bay and behind the present-day coastline between the Wooramel River and Carnarvon. Many of the present-day stromatolites in Hamelin Pool are growing on submerged ridges of Bibra Limestone (Playford, 1980), but further offshore the Bibra Limestone is apparently absent (Logan, Read and Davies, 1970). The Gladstone embayment is the type area of the Bibra Limestone. It is generally less than 1 m thick and is present at elevations ranging between a couple of metres below and above sea level.

Radiocarbon dates from the Bibra Limestone were inconclusive (Logan, Read and Davies, 1970). It probably formed during the last Pleistocene interglacial high sea-level stand, 120 000 to 130 000 years ago (van de Graaff and others, 1983), at the same time as the dated Bundera Calcarenite in the Lake MacLeod area.

HAMELIN COQUINA

The Hamelin Coquina was named and described, but not defined, by Logan (1974). It consists almost solely of shells of the small bivalve *Fragum erugatum*. The shells are about one third of the normal mature size because of hypersaline conditions, but are very abundant due to a lack of competing organisms. They form indurated, semi-indurated and unconsolidated beach ridges up to about 3 m thick, a kilometre wide and several tens of kilometres long, around the margins of Hamelin Pool and Lharidon Bight (Fig. 9). Minor outcrops are present elsewhere, as for example at Goulet Bluff. Logan did not specify either a type locality or a type section. The area near Flagpole Landing, and specifically the quarry at Boolagoorda, is here taken as the type locality , as a type section *sensu stricto* is impractical.

Consolidated Hamelin Coquina has been used to construct several buildings in the Shark Bay area, notably Hamelin homestead. It is quarried and cut into large bricks with saws. Unconsolidated coquina is used for road building and decorative purposes. Controls on its use now exist, and removal outside the Shark Bay area is prohibited. The Hamelin Coquina is also useful as a limited-supply, shallow-depth aquifer in some beach wells around Hamelin Pool.

MISCELLANEOUS NAMED CAINOZOIC UNITS

WALATHARRA FORMATION

The Walatharra Formation (Condon and others, 1956) consists of medium- to thick-bedded limestone-pebble conglomerate. The conglomerate contains numerous laterite fragments and is calcreted. The unit is only known from the type locality on the eastern limb of the Giralia anticline about 11 km west of Giralia homestead, where it is about 30 m thick and unconformably overlies the Trealla Limestone. The Walatharra Formation is unfossiliferous, and could be either Pliocene or Pleistocene in age. It is significant because it is the youngest known deposit to have been affected by the folding of the Giralia Anticline.

NADARRA FORMATION

The Nadarra Formation (Condon, *in* McWhae and others, 1958), is a thin, calcareous, fine-grained unit generally associated with major drainages in the eastern Carnarvon Basin between Williambury, Yalbalgo and Dairy Creek. It consists of structureless to poorly bedded, fine-grained calcilutite and variably calcareous, calcreted mudstone and siltstone, with minor fine-grained gritty and silty sandstone. It is commonly silicified, with a white to light-grey, opaline or porcellaneous appearance. Poorly developed and preserved, possible fresh-water stromatolites are present in the unit near Gubbiddy Well on Eudamullah Station. In the Gubbiddy Well area and in Nyarra Creek, it is clearly a valley-fill unit, but elsewhere it forms low to moderately high

mesas or ridges. The type section is about 5 km north-northeast of Nadarra Well on Williambury Station.

The Nadarra Formation is unconformable on older units, with a commonly irregular basal contact, and its age is Pliocene to Pleistocene.

"JOOLABROO FORMATION"

The name "Joolabroo Formation" was initially used by Condon (1954) for high-level, semi-consolidated older alluvium in the area of the Lyndon–Minilya Rivers within the Merlinleigh Sub-Basin. It was later extended to the Byro Sub-Basin by Konecki and others (1958). It was ignored by Condon (1968) and has not been used in the present study because, as mapped, it undoubtedly includes alluvial, colluvial, diluvial and residual deposits, and is gradational into present-day deposits.

SUPERFICIAL DEPOSITS

Cainozoic sediments of residual, alluvial, eolian and mixed origins cover much of the Carvarvon Basin. Except in coastal areas, they are mainly superficial and have not been named. On Plate 1, the superficial sediments have been grouped into broad units according to their inferred origin by alluvial, eolian, residual, lacustrine or coastal processes, and the reader is referred to the individual 1:250 000 map sheets for greater detail concerning the superficial sediments. Distinction of units has been largely based on photo patterns and morphology rather than lithological differences visible on the ground, so units are primarily morphostratigraphic, in the sense of Frye and Willman (1962).

LATERITE AND SILCRETE

Pisolitic and locally vermiform laterite up to a few metres thick, with a pallid zone beneath, occurs as mesa cappings and in breakaways in virtually all pre-Miocene outcrop areas and is thought to underline most of the extensive sandplain areas of the Carnarvon Basin. Pisolitic and laminar silcrete is similarly distributed. On 1:250 000 map sheets, intensely ferruginized and/or silicified rock has commonly been included with laterite and silcrete.

Formation of laterite and silcrete in the Carnarvon Basin was approximately synchronous, because in some areas laterite clasts are incorporated within silcrete, while the reverse occurs, although less commonly, in other areas. Development of laterite and silcrete appears to have been controlled to a large extent by the nature of the underlying bedrock. There is preferential development of silcrete over the Windalia Radiolarite and other clayey bedrock, and in the area south of the Murchison River near Yallalong there is preferential development of laterite on Precambrian bedrock and silcrete on Phanerozoic rocks. Over much of the Byro Sub-basin, laterite is present on slopes and grades laterally into silcrete on flat hilltops, indicating topographic controls. The nature of these controls is not clear.

Lateritization and silcretization occurred in at least two major phases and one minor phase. In the Giralia Range, laterite is locally present on the Eocene Giralia calcarenite and beneath the Miocene Lamont Sandstone and Trealla Limestone (van de Graaff and others, 1980). Elsewhere north of the Gascoyne River, the Eocene Merlinleigh Sandstone is either lateritized or silcreted, while the few outcrops of Trealla Limestone away from the coastal anticlines are not. It is therefore concluded that in this area lateritization and silcretization occurred in the Oligocene, when there was a hiatus in marine deposition to the west and north. South of the Gascoyne River, the Miocene Lamont Sandstone and ?Miocene Pindilya Formation are locally lateritized (van de Graaff and others, 1983), indicating post-middle Miocene lateritization. It is not known whether there are two distinct phases of lateritization or whether the phases are gradational, with lateritization simply occurring at a later date further south. No evidence has been found favouring either hypothesis in the transitional area near Kennedy Range (Hocking, Williams, Moore and others, 1985). The fact that the Lamont Sandstone is intensely silicified in the Chargoo and Giralia Anticlines suggests there may have been minor/incipient silcretization during or shortly after its deposition in the northern Carnarvon Basin.

Evidence of a third phase of lateritizastion is present near Kalbarri. In this area, the main phase of lateritization pre-dates the incision of the Murchison River gorge. However, laterite is present on slopes leading down to the Murchison River and surrounding Meanarra Hill. This post-dates incision of the gorge and indicates a third phase of lateritization. It is probably of late Pliocene to Pleistocene age (Hocking and others, 1983).

DURICRUST CALCRETE

Pisolitic, laminar and "brecciated" calcrete is extensively developed as a duricrust on calcareous rocks. Detrital laterite fragments are present within the calcrete duricrust in some areas, and well-developed palaeodrainages in calcreted Toolong Calcilutite are truncated by Tamala Limestone south of Shark Bay, which fixes the time of calcretization as Pliocene to Early Pleistocene. Minor calcretization has occurred in most superficial deposits (especially in coastal areas) forming pisolitic, nodular, and vermiform concretions. These are probably continuing to form.

VALLEY CALCRETE

Valley or groundwater calcrete (Mann and Horwitz, 1979) is present in many of the major drainages and palaeodrainages, mainly along or near the eastern margin of the Carnarvon Basin. On the map accompanying this bulletin it has been grouped with the Nadarra Formation, a Pleistocene to ?Pliocene lacustrine limestone to mudstone. Mann and Horwitz (1979) considered that the development of valley calcrete in Western Australia began in an arid period with sluggish groundwater movement at some time greater than 36 500 years B.P., based on radiocarbon dates from a profile near Yeelirrie in the central Yilgarn Block. In the Carnarvon Basin, development may have begun in the Pliocene, at the same time as duricrust calcrete formed. It certainly continued through the Pleistocene, as some consolidated colluvium (mapped as *Czc* on most 1:250 000 sheets and thought to be of Pleistocene age) is extensively calcreted, sufficiently so that Condon (1954) elevated calcareous consolidated colluvium to formation status as the "Joolabroo Formation" (this name has not been used on the current series of 1:250 000 map sheets). Valley calcrete may still be developing, as relatively unconsolidated alluvium in the Ashburton River near Nanutarra homestead and in the Murchison River north of Bompas Hill shows incipient calcretization.

Valley calcrete is important as a shallow-depth aquifer in some areas, suitable for domestic and stock water (Nyang homestead, Lyndon Station, Yallalong Station). A second potentially important aspect is as a host for uranium mineralization. Valley calcrete is uraniferous at Yeelirrie and at Jailor Bore on Lyndon Station, but both areas are well within Precambrian outcrop. The limited amount of exploration to date within the Carnarvon Basin has not been successful (Carter, 1981).

OTHER UNNAMED SUPERFICIAL DEPOSITS

Unconsolidated to semi-consolidated, dominantly sandy alluvium is present along major drainages. Semi-consolidated to consolidated alluvium commonly forms terraces above present-day river levels, and is more than 20 m thick in the Wooramel River gorge, the thickest known development. Alluvial deposits grade laterally into colluvial, diluvial (sheet-flood), and residual deposits, and all have undergone varying amounts of eolian reworking. In its most pronounced form, the eolian reworking has produced a dune and playa terrain in many areas, such as east of Exmouth Gulf. Most of these deposits are clearly Holocene, but some are of Pleistocene age and in some areas may extend into the Pliocene.

Eolian deposits cover much of the Carnarvon Basin and have two dominant morphologies. South of the Wooramel River a largely featureless sand plain, of eolian and residual origin, forms the uppermost layer of the Victoria Plateau. Minor longitudinal and hummocky dunes are locally present. North of the Wooramel River, there are several vegetated longitudinal dune fields of varying size. In inland areas, they consist of quartz sand, stained to a deep red-brown colour, but approaching the coast they are progressively more calcareous and lighter coloured. The substrate beneath the dunes varies from consolidated older sediment to relatively unconsolidated sediment, generally near the centre of dunefields. The dunes are a relic feature and are thought to have formed during an arid phase 16 000 to 25 000 years B.P. (Bowler and others, 1976).

The three notable Quaternary coastal features of the Carnarvon Basin are Shark Bay, Lake MacLeod and Exmouth Gulf. These have been the subject of detailed studies by the University of Western Australia. The Quaternary environments of Shark Bay have been described in detail by Logan, Davies and others (1970) and Logan, Read and others (1974). Playford and Cockbain (1976) and Playford (1980) gave details of the stromatolites and environmental controls on them, in Hamelin Pool. Logan and others (1976) summarized the Quaternary environments of Shark Bay and Exmouth Gulf. Johnson (1982) described the Gascoyne River delta at Carnarvon.

Further, more specific details on superficial deposits are contained in individual explanatory notes (Table 1).

CHAPTER 11

Structural Geology

The Carnarvon Basin extends from the Perth Basin in the south to the Canning Basin in the north (Fig. 1). In the south, the Precambrian Northampton Block separates the Carnarvon Basin (to the west of the block) from the Perth Basin (to the east) in much of the onshore area, although Triassic sediments related to the Perth Basin do extend into the southernmost Carnarvon Basin south of Kalbarri. In the remainder of the onshore area, the Ajana Fault System (the northeastwards continuation of the faults bounding the Northampton Block) is taken as the boundary between the Carnarvon Basin and the Coolcalalaya Sub-basin of the Perth Basin (Playford and others, 1976), although there is no significant difference between the sediments on either side of the boundary. Offshore, the Geelvink Fault separates the Carnarvon Basin from the Abrolhos Sub-basin of the Perth Basin (Megallaa, 1980). The boundary of the Carnarvon Basin with the Canning Basin is taken at the De Grey Nose, following Playford and others (1975) rather than Robertson and others (1978) who included the Beagle Sub-basin (which lies east of the De Grey Nose) in the Carnarvon Basin. The eastern boundary of the Carnarvon Basin is the Precambrian craton, while in the west the Carnarvon Basin extends to the boundary between continental crust and oceanic crust.

The sub-basins of the Carnarvon Basin (Fig. 2) are readily divided into two groups, corresponding approximately to the onshore and offshore parts of the basin. The first group is north to northwest trending and contains predominantly Palaeozoic sediments, with a westward-thickening Cretaceous and Cainozoic veneer. The constituent sub-basins are the Gascoyne, Merlinleigh, Byro and Bidgemia Sub-basins and they are generally referred to as the Palaeozoic Sub-basins (Thomas and Smith, 1976). The Wandagee-Yanrey and Ajana Ridges divide the Gascoyne Sub-basin from the Merlinleigh Sub-basin. The second group of sub-basins trends northeast and consists of the Exmouth, Barrow and Dampier Sub-basins, the Rankin Platform, the Kangaroo Syncline, and the Exmouth Plateau Arch. They contain very thick Mesozoic sequences hence the term Mesozoic Sub-basins. The Peedamullah and Lambert Shelves are marginal shelves adjoining these sub-basins. The Mesozoic Sub-basins were tectonically active until the Early Cretaceous, and quiescent in the Late Cretaceous and Cainozoic. In the latter phase, no sub-basins can be recognized on structural or sedimentological grounds, and the Mesozoic sub-basins effectively form a single unit, extending along the North West Shelf of Australia.

PALAEOZOIC SUB-BASINS

GASCOYNE SUB-BASIN

The Gascoyne Sub-basin is an elongate platform of flat-lying to gently-tilted rocks which extends from the southernmost Carnarvon Basin to Exmouth Gulf. The infill is primarily Silurian, with Devonian, Lower Carboniferous and minor Permian remnants in the northern part of the sub-basin, and a westward-thickening Cretaceous and Cainozoic wedge. The sub-basin is bounded on the northwest by the Rough Range Fault, on the southwest by the Geelvink Fault, on the west by the Bernier Platform and on the east by the Wandagee-Yanrey and Ajana Fault Systems. The Wandagee-Yanrey Ridge and the Ajana Ridge form the easternmost parts of the Gascoyne Sub-basin.

The sub-basin is block faulted into a series of horsts, half-grabens and possibly shallow grabens. The deepest known part of the basin (except in the transitional area immediately west of Kennedy Range, discussed below) is beneath the Giralia Anticline near the Giralia Fault. Three localities are known where all pre-Cretaceous sediments have been eroded. These are the Yanrey High (at the culmination of the Wandagee-Yanrey Ridge and drilled by Yanrey 1), and small areas on Mia Mia and Woodleigh Stations. On Mia Mia, a mag-

netic anomaly near the homestead was drilled in connection with kimberlite exploration, and granitic basement was encountered at 153 m (Gregory, 1982). Water bores 5 km and 8 km away encountered Devonian sediments. The Precambrian is probably a small horst block related to a change of direction of the Wandagee Fault System, which occurs in this area. On Woodleigh a small but intense gravity high near the homestead was drilled, and granitic basement was intersected at 171 m beneath Cretaceous sediments (Richardson, 1981). Jurassic and Silurian sediments are known less than 15 km away, indicating that it is a small horst block which formed in the Middle or Late Jurassic. There is no obvious reason for its presence.

The Wandagee-Yanrey Ridge is a north-trending structurally elevated ridge at the easternmost side of the Gascoyne Sub-basin. It extends from (approximately) Hutton Creek on KENNEDY RANGE to the north end of Exmouth Gulf, where it is truncated by the Long Island Fault System. On the east it is bounded by the Wandagee Fault System, a major normal-fault system with a throw on the easternmost fault of several kilometres. The alkali-picrite intrusives in the Wandagee area occur where the Wandagee Fault (*sensu stricto*) attains its greatest southern throw. The western boundary of the Wandagee-Yanrey Ridge is the Marrilla Fault, a large, west-block-down normal fault. This fault appears to die out on northern KENNEDY RANGE, as neither it nor the Wandagee-Yanrey Ridge can be recognized south of Hutton Creek.

The Ajana Ridge extends approximately northwards from the Northampton Block to near the Jimba Syncline. It is poorly defined because of very sparse data. The eastern boundary is a series of east-block-down normal faults, the Ajana Fault System, which generally places Silurian sediments on the west against Permian sediments on the east. The western boundary is difficult to place, as only Silurian sediments are present. Probably, the basin gradually deepens over a series of west-block-down faults.

Between the Gascoyne River and Hutton Creek, no single fault system separates the Gascoyne and Merlinleigh Sub-basins. Instead, an *en echelon* series of faults links the Ajana and Wandagee-Yanrey Fault Systems, and the Palaeozoic sequence west of the faults is thicker than elsewhere. Although they appear to be normal faults, their pattern suggests that they were controlled by a major northwest-oriented transcurrent-stress direction. This direction is a common structural orientation in Western Australia, shared by greenstone belts in the eastern Yilgarn Block, the Meckering Line, the northern boundary of the Gascoyne Province, the Fitzroy Trough, and the Urella Fault.

The Hardabut Fault separates the southernmost Gascoyne Sub-basin from the Northampton Block. The name was originally applied to a small reverse fault, visible in the bed of the Murchison River (Johnstone and Playford, 1955; Playford and others, 1976). Hocking and others (1983) later included the large normal fault which underlies and is apparently continuous with the reverse

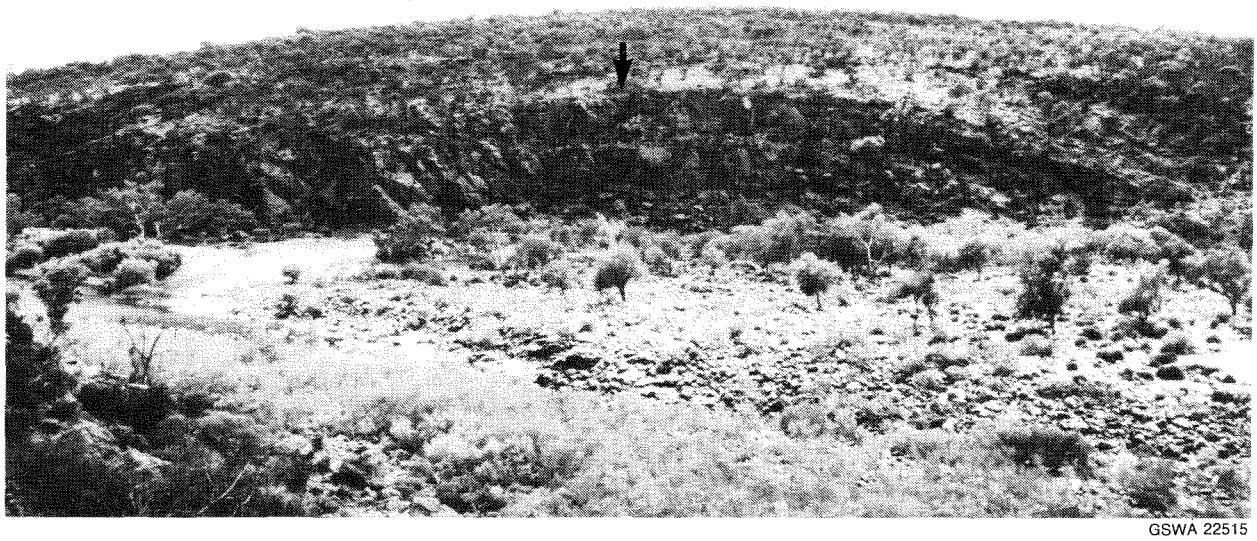


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Figure 121. Hardabut Anticline, north bank of Murchison River. Precambrian is in lowermost right-hand corner. "Keystone" jointing occurs in anticline core.

fault. On GERALDTON, the Tumblagooda Sandstone crosses the buried-fault trace (shown by a steep-gravity profile) without disruption, indicating that no movement occurred after the Silurian, but on AJANA there was probably significant post-Silurian movement. The total normal movement on AJANA was probably about 1000 m with a possible maximum throw of 2300 m (Hocking and others, 1983). The reverse movement formed a small anticline, the Hardabut Anticline (Fig. 121), centred on the Murchison River and by analogy with the coastal anticlines further north, it was formed in the Miocene to Pleistocene. Reverse movement is inferred because of the apparent uplift of the Silurian sequence to the west.

The remarkably straight line of the Zuytdorp Cliffs may be fault controlled (Butcher and others, 1984). However, marine seismic lines normal to the coastline, and close to it, show no indication of a major fault. If present, the fault does not have a large throw and is quite close to the coastline (1–2 km). Along the coastline, the Tumblagooda Sandstone is not displaced between Second Gully and Red Bluff, indicating either that there is no fault in the Kalbarri township area (where it would logically cross the coastline) or that the fault is offshore from Red Bluff, between the end of marine seismic lines and the coast. Accordingly, the fault is not shown on Plates 2 or 3.

The main phase of faulting in the Gascoyne Sub-basin took place in the Middle Triassic to Jurassic (based on the ages of preserved sequences, the presence or absence of faulting in those sequences, and the ages of major sediment packages in adjoining areas), but reverse movement occurred on many faults in the Cainozoic. This caused anticlinal doming over faults on YANREY–NINGALOO and WINNING POOL–MINILYA and the Hardabut Fault on AJANA. The resultant "coastal anticlines" are described in Chapter 2.

MERLINLEIGH SUB-BASIN

The Merlinleigh Sub-basin is a half graben, bounded on the west by the Wandagee, Kennedy and Ajana Fault Systems and infilled primarily by Permian sediments. Devonian and Lower Carboniferous sediments occur in the northern part of the sub-basin and Silurian sediments in the western part. A veneer of Cretaceous sediments masks Palaeozoic sediments at the northern end of the sub-basin where it grades into the Peedamullah Shelf. The basin is more than 4 km deep beneath Kennedy Range and Wandagee Hill. It deepens northwards from the Carrandibby Inlier to the Kennedy Range, and then shallows northwards from the Minilya River. The boundary with the Peedamullah Shelf is placed at about 23°15'S, where the Devonian and Lower Carboniferous sequence has been totally eroded in places.

Faulting within the basin is primarily north-trending, east-block-down ?normal faulting. Several areas of locally intense faulting occur, for example, immediately west of Donnelly's Well, near Wolgangie Bore, and near Lyons River homestead.

The Merlinleigh Sub-basin is dominated by the large syncline beneath Kennedy Range. Other large synclines are near the Minilya River, centred on Wandagee Hill, and near the Lyndon River south of Mia Mia homestead. Drag anticlines and synclines have developed near major faults. These probably formed as a result of irregularities in the fault plane, in the manner described by Hamblin (1965).

The Kennedy Fault System consists of the largest of the *en echelon* faults on the west side of Kennedy Range and its northwards continuations. As with other faults in the Carnarvon Basin, its main period of activity was probably Jurassic, but some normal movement probably dates back to the Permian (see the section on the Kennedy Group in Chapter 3), and reverse movement occurred in the Cainozoic (Fig. 122), presumably allied with the reverse movement which formed the coastal anticlines.

BYRO SUB-BASIN

The Byro Sub-basin is a downfaulted, northwards-deepening synclinal area, containing at least 1600 m of Permian and ?Upper Carboniferous sediments over an unknown thickness of Proterozoic sediments. The eastern boundary of the Sub-basin against the Precambrian is partly faulted (the Meeberrie Fault System) and partly unconformable. On BYRO and YARINGA, the sub-basin is stratigraphically continuous on the west with the Merlinleigh Sub-basin and the Coolcalalya Sub-basin (Perth Basin), and the boundary is placed along a probable, major, northwest-trending fault. The boundary is disrupted by a north-plunging ridge of metamorphosed Proterozoic sediments in the palaeodrainage valley west of Muggon homestead. The sub-basin is bounded on the northwest by the Madeline Fault System.

A northeast-trending splay fault of the Darling Fault divides the Byro Sub-basin into a northern and southern half. The southern part of the sub-

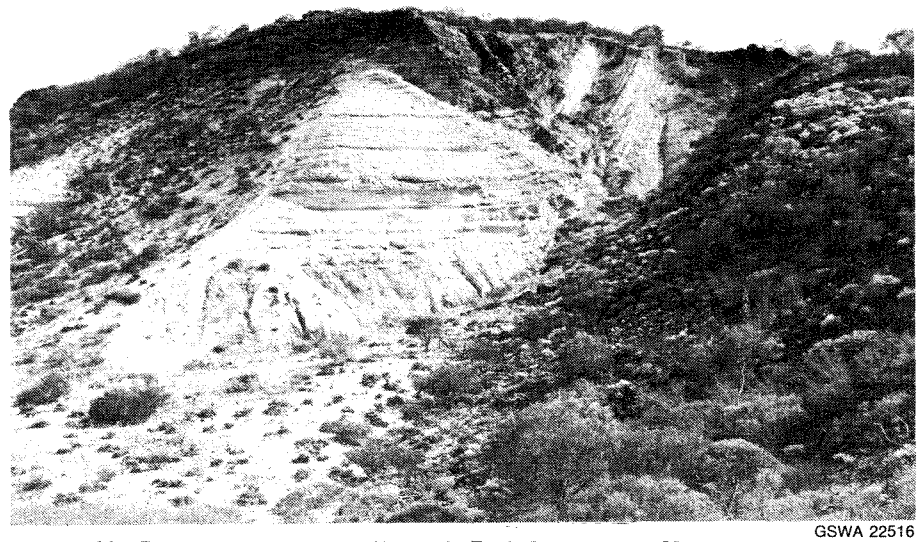

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Figure 122. Reverse movement on Kennedy Fault System near Muderong (Twins) Bore. View north with Birdrong Sandstone, Windalia Radiolarite and Muderong Shale (on left) against Kennedy Group (on right). Main movement on fault was down to the east, drag on Cretaceous sequence indicates later reverse movement.

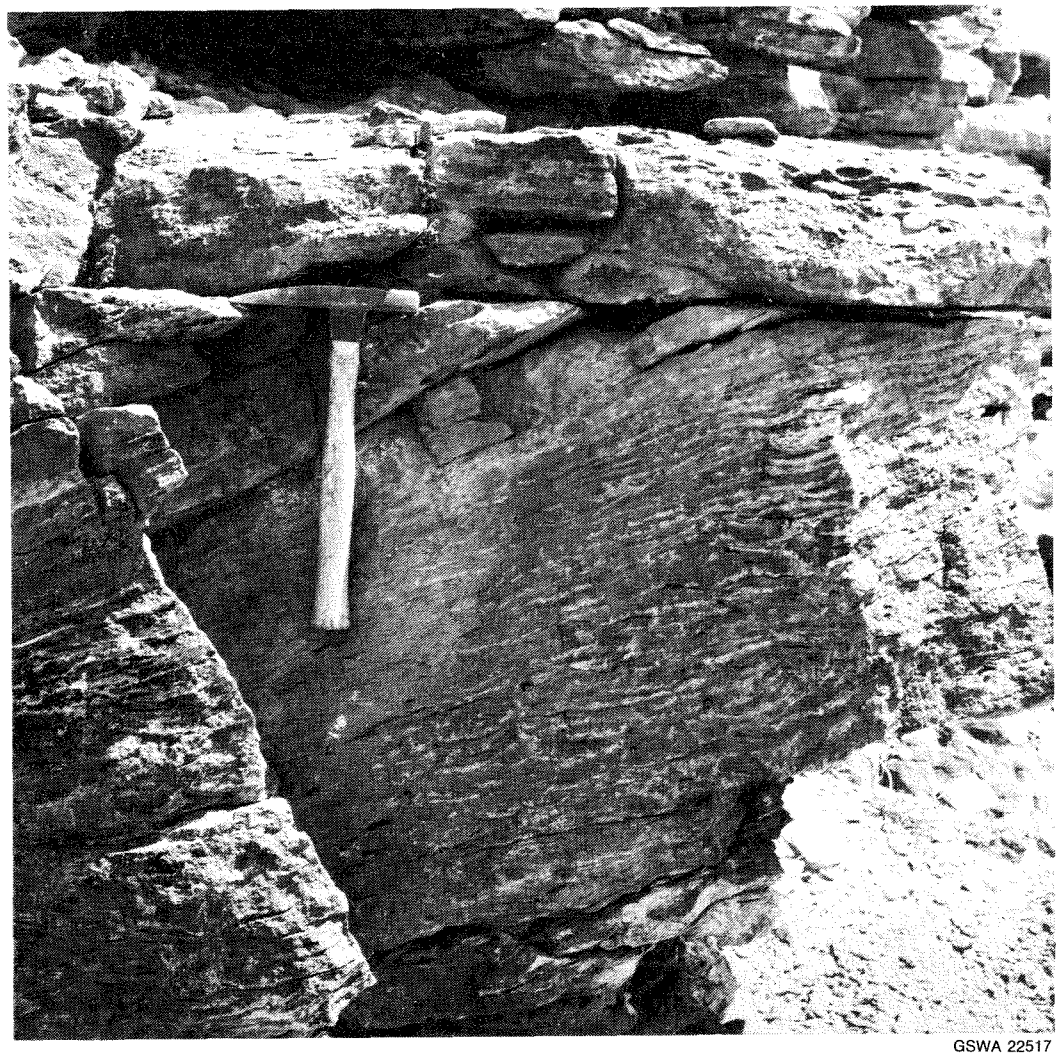

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Figure 123. Moogooloo Sandstone south of Callytharra Spring, with angular unconformity at level of pick. Dip below is tectonic and not part of a foreset.

basin is a relatively simple synclinal downwarp, except for the Curbur Syncline, but the northern, downfaulted part contains several synclines and the Ballytharra Hill Anticline. Additionally, much more faulting can be recognized in the northern part of the sub-basin, but this may be due in part to more widespread outcrop. Drag anticlines and synclines are developed along the Madeline Fault.

The Carrandibby Inlier is a large area of Precambrian rocks which separates the Byro Sub-basin from the southern Merlinleigh Sub-basin. It is bounded on the southeast by the Madeline Fault. On the northern and western sides, it is onlapped by the Lyons Group. At the southern end, the inlier is onlapped by the Lyons or Wooramel Groups (see below). An anticlinal trend of shallow basement, the Weedarra Ridge, extends northwards from the inlier to the Weedarra Inlier.

The Madeline Fault System consists of the Madeline Fault and its southwestern and northeastern extensions. It throws down to the east, with the greatest throw near Mount Madeline, where the Byro Group abuts the Carrandibby Inlier. The main period of movement on the fault system was presumably Triassic–Jurassic (as in the Merlinleigh and Gascoyne Sub-basins), and there is no indication of Cainozoic reverse movement.

Two lines of evidence suggest that Permian movement occurred. Firstly, there is an angular unconformity within the Moogooloo Sandstone south of Callytharra Spring (Fig. 123). This must have been caused by syndepositional movement on the Madeline Fault. Secondly, severe erosion of the Lyons Group and Callytharra Formation occurred prior to deposition of the Wooramel Group at the south end of the Carrandibby Inlier — the Wooramel Group locally rests directly on Precambrian basement. This indicates that the Carrandibby Inlier was a positive topographic feature in the early to middle Artinskian, due to significant movement on the Madeline Fault. It is uncertain whether the inlier remained a positive feature through the late Artinskian — the Byro Group shows no marked facies changes between the Byro and Merlinleigh Sub-basins, which could be expected if the Carrandibby Inlier formed a major island.

BIDGEMIA SUB-BASIN

The Bidgemia Sub-basin is a northwards continuation of the Byro Sub-basin. The eastern boundary is unconformable except for a faulted contact in the Bush Creek Syncline. The northern part of the basin is a half graben, faulted against Precambrian rocks in the Weedarra Inlier and west of Eudamullah. South of the Weedarra Inlier, the western boundary is less distinct, and extends along a subcropping basement ridge (delineated by dips in the Permian sequence). This is called the Weedarra Ridge (Condon, 1965b), which links the Carrandibby and Weedara Inliers. The sub-basin is infilled primarily with Upper Carboniferous-Lower Permian Lyons Group. The Callytharra Formation and Wooramel Group occur in downfaulted synclines (the Bush Creek and Congo Synclines), strike ridges, and drag synclines along the western margin of the sub-basin. Proterozoic sediments do not underlie the Phanerozoic sequence except for a small area of Bangemall Group sediments in the Minginoo Inlier.

The Permian sequence is extensively faulted, mostly by north-trending, east-block-down faults. These faults may be in part related to compaction in the Lyons Group, rather than deep-seated crustal fracture. The Congo Syncline is thought to have formed in this manner, by large-scale, northwards sliding of the Permian sediments off the basement high of the Carrandibby Inlier.

The Weedarra Inlier is a structurally elevated area of Precambrian rocks. The eastern boundary is an irregular system of faults, but the western boundary (although very straight) appears unconformable. A possible explanation for this is given below, in the section on the Darling Fault.

MESOZOIC SUB-BASINS

Structural sub-divisions of the Mesozoic sub-basins are shown in Figure 124.

EXMOUTH SUB-BASIN

The Exmouth Sub-basin is the most southerly of the northeast-trending Mesozoic Sub-basins and is bounded on the southeast by the Rough Range Fault. This was active in the Jurassic, resulting in the deposition of several kilometres of Jurassic claystone (more than 3500 m in Cape Range 2). The Yardie Trend, a high trend similar to the Alpha Trend, divides the sub-basin into two nearly equal parts. The eastern part is a series of half grabens with possibly more than 6000 m of Triassic-Jurassic sediments (Thomas and Smith, 1976, Fig. 13), but the western part appears more synformal although it has not been drilled. The sub-basin is bounded on the west by the Mandu Ridge (Megallaa, 1980) and on the north by the Kangaroo Syncline.

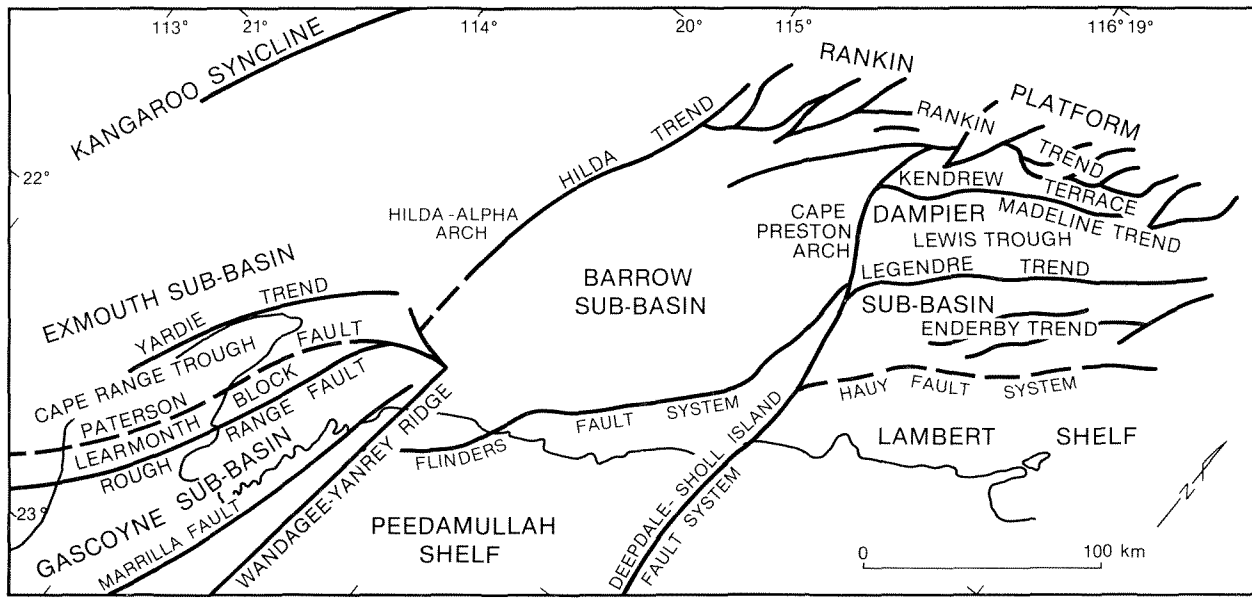

Figure 124. Structural elements: Exmouth, Barrow and Dampier Sub-basins.

The Rough Range Fault is a large, arcuate, normal fault with a throw locally greater than 4000 m. The fault extends well out to sea to the southwest (Megallaa, 1980, Fig. 5), and wraps around the Wandagee-Yanrey ridge to the northeast. Repeated normal movement occurred in the Cainozoic, resulting in the formation of anticlines along the strike of the fault.

The Paterson and Cape Range Faults are similar to the Rough Range Fault, with a similar history, but have a smaller throw. The amount and lateral extent of reverse movement was presumably greater on these faults than on the Rough Range Fault, because the Cape Range Anticline, with a length of more than 100 km and a vertical closure of more than 300 m, is substantially larger than the Rough Range Anticline.

The faulting produced a series of half grabens, deepening to the west. The half grabens west of the Paterson Fault, and between the Paterson and Rough Range Faults are called, respectively, the Cape Range Trough and the Learmonth Block. The sandy Lower Jurassic sediments, which occur in the Cape Range Trough but not the Learmonth Block, indicate that the former developed first, as shown in Figure 80. The Learmonth Block developed in the Middle Jurassic, when faulting was more severe.

The Yardie Trend is the southern continuation of the Hilda Trend, offset to the west by the Long Island Fault System. It is an anticlinal trend produced by faulting and probably developed in the Middle Jurassic, by analogy with other Rankin Platform activity.

BARROW SUB-BASIN

The Barrow Sub-basin is the northeast-trending Mesozoic Sub-basin between the Exmouth Sub-basin (to the southwest) and the Dampier Sub-basin (to the northeast). It was continuous with both in the Triassic, but the tectonism which affected the Dampier Sub-basin in the Jurassic did not extend to the Barrow Sub-basin. This was because of the Cape Preston Arch, which is here taken as the eastern boundary. The sub-basin is separated from the Peedamullah Shelf to the southeast by the Flinders Fault System, which grades into the Long Island Fault System in the extreme south of the basin. The Rankin Platform adjoins the basin to the northwest. The structural simplicity of the sub-basin is reflected in the monotony of the contained sediments: uniform claystones, except for minor sandstones in the Middle Jurassic and the extensive sandy Neocomian Barrow Group.

The Flinders Fault System is a zone of numerous, commonly anastomosing, normal faults which, although probably inactive during most of the Triassic, has a complex Jurassic and Cretaceous history. Generally, more of the section is preserved in the more northwesterly fault blocks. In the higher, southeastern blocks erosion was more severe and deposition commenced later, with some blocks not covered until the Late Cretaceous (Wiseman, 1980). The accumulated throw over the fault system is several kilometres.

The Cape Preston Arch was named by Mollan and others (1969), who considered it to be a fundamental basement high. It appears to restrict the

southerly continuation of the horsts and grabens of the Dampier Sub-basin, and seismic sections show that beds wedge out over the arch, with a pronounced Palaeozoic sediment extension at shallow depth. To the south, it grades into the Deepdale and Sholl Island Fault Systems. These are north-south-orientated fault systems with substantial westerly downthrows which continue southwards into the Precambrian hinterland.

DAMPIER SUB-BASIN

The Dampier Sub-basin is the northernmost of the Mesozoic sub-basins of the Carnarvon Basin, lying between the Barrow Sub-basin to the southwest and the Beagle sub-basin of the Canning Basin to the northeast. The basin is bounded by the Rankin Platform (northwest), the Cape Preston Arch (southwest), the Lambert Shelf (southeast) and the De Grey Nose (northeast). It developed as a distinct entity in the Jurassic, when the tectonism associated with Gondwana breakup produced a series of ridges, terraces and troughs which Veenstra (1985) discussed in some detail. These persisted until the Late Cretaceous, when a uniform sediment blanket covered all the Mesozoic sub-basins. The sub-basin is readily subdivided unlike the Barrow Sub-Basin.

The De Grey Nose is a structural high which was a positive topographic feature during most of the Mesozoic, as only thin intermittent sedimentation occurred over it before the Late Cretaceous marine transgression. It probably extends on to the Precambrian craton, as all deltas in the Dampier Sub-basin developed from the De Grey Nose region, which suggests that it controlled the major fluvial systems.

The Lewis Trough developed in the Jurassic, as Triassic sediments show no variation in thickness over the trough (Crostella and Barter, 1980) but Jurassic strata thicken markedly into the trough, with a sequence several kilometres thick. The infill is mostly shale, with sand fringing the eastern margin and concentrated near the De Grey Nose. The structural style appears simple, and the trough extends the length of the Dampier Sub-basin. Seismic correlations into the Barrow Sub-basin are doubtful.

The Kendrew Terrace is an extensively faulted half graben on the margin of the Rankin Platform. It was initially identified by apparent sagging of Cretaceous sediments, but better quality seismic and gravity surveys and well data have since indicated that the terrace developed in the Jurassic.

The Madeleine Trend is an anticlinal high trend between the Kendrew Terrace and Lewis Trough. It extends from the De Grey Nose to the Barrow Sub-basin. Though probably active through most of the Mesozoic, its basinal location resulted in only brief emergence, with relatively continuous deposition except for the regional Albian/Aptian unconformity. It existed in the Lower Jurassic, as sediments of that age thin over the structure and possibly onlap it. Several separate culminations exist, some of which (*e.g.* Angel) have been drilled.

The Legendre Trend is an anticlinal high trend similar to the Madeleine Trend, on the southeastern side of the Lewis Trough. It extends from the De Grey Nose to the Barrow Sub-basin, but seismic correlation into the latter is poor. It also originated from deep-seated faulting and has several separate culminations, one of which (Legendre 1) contains a small oil accumulation. Because the Legendre Trend is nearer to the basin margin than the Madeleine Trend, tectonic activity resulted in more numerous and longer diastems.

The Enderby Trend is a high trend along the southeastern side of the Dampier Sub-basin. The southeastern boundary of the trend is an east-block-down fault system (the Enderby Fault System), but the trend itself is a series of faults which results in progressively lower terraces towards the Lengendre Trend. Because the Enderby Trend is close to the basin margin, the section is condensed, erosion has been severe, and periods of tectonic activity are difficult to place. All Palaeozoic sediments have been eroded from the trend northeast from Enderby 1 (see Hampton 1, Lawley 1, Hauy 1). Strickland 1 was in a graben which separates the Enderby Shelf. This graben is in a similar position to, but is wider than, the Karratha Graben shown by Knopsen and McGann (1985).

RANKIN PLATFORM

The Rankin Platform is an elongate structurally high area bounding the Exmouth, Barrow and Dampier Sub-basins. It was initially identified solely as a large gravity high. Subsequent seismic surveys indicated the platform's structural origin. Later, drilling and better quality data revealed the complex nature of the platform. It consists of uplifted, severely faulted, Triassic and Lower Jurassic sediments, unconformably overlain by Upper Cretaceous and Cainozoic sediments, with some drape closure. The Rankin Platform changes direction northwest of Barrow Island, allowing the

subdivision of a northern Rankin Trend and a southern Hilda Trend. The Hilda Trend is itself offset by the Long Island Fault System, and the southwesterly offset (in the Exmouth Sub-basin) is termed the Yardie Trend.

The Rankin Trend is an *en echelon* arrangement of northwesterly dipping fault blocks formed by two intersecting fault systems. The dominant fault set strikes at between 070° and 080°, and orients the trend. The second set strikes at 030° to 040°. Throw on some of the faults is in the order of kilometres. The eastern edge is not uniform, and isolated lower blocks or terraces are common (*e.g.* Eaglehawk block, Tidepole block). The horsts are commonly separated by grabens. The trend extends approximately 200 km from northeast of the Eaglehawk structure to near the Gorgon structure.

The main period of tectonism was during the Middle Jurassic, deposition being continuous until the Bathonian (North Rankin 4), and recommencing in the Kimmeridgian (Egret 1). It is uncertain whether displacement in the Cretaceous sequence is due to sedimentary drape or to Cretaceous reactivation of the faults, although movement certainly continued on some faults until the Late Cretaceous. Variation in throw along the Rankin Trend resulted in large variations in fault-block elevation which led to variable erosion. For example, all the Jurassic and some Triassic was removed in the Goodwyn area while some Jurassic sediments still exist in a crestal position in North Rankin Field. Similarly, the blocks were inundated at different times during the regional Cretaceous transgression, those in the south as early as Valanginian, while those in the north were still emergent in the Barremian (Wiseman, 1979).

The Hilda Trend is a southern extension of the Rankin Platform. Near the Gorgon structure, the more easterly oriented fault system of the Rankin Trend dies out, but the meridionally oriented system continues, forming the Hilda Trend. The major differences between the Hilda and Rankin Trends are: in the former, the single fault system results in a different strike (about 030°); the fault blocks do not dip to the northwest; and faults throw down to both the east and west, resulting in a more anticlinal shape. The last mentioned has resulted in the name Hilda-Alpha Arch being applied to the area near Hilda 1A.

The Hilda Trend, like the remainder of the Rankin Platform, probably developed mostly in the Middle Jurassic. In Hilda 1A, any Lower Jurassic sediments which may have been present have been eroded, and Tithonian sediments rest directly on Triassic sediments. Erosional hiatuses after the early Neocomian were probably due to epeirogenic changes rather than tectonism.

EXMOUTH PLATEAU

The most comprehensive description of the Exmouth Plateau area is by Exon and Willcox (1980). Two major structural elements are present, the Exmouth Plateau Arch and the Kangaroo Syncline, and the depth to crystalline basement is probably about 12 km.

The Kangaroo Syncline separates the Exmouth Plateau Arch from the remainder of the Carnarvon Basin, and has been regarded as a heavily faulted graben with a central trough flanked by progressively higher fault terraces. (Wright and Wheatley, 1979; Exon and Willcox, 1978, 1980).

However, reinterpretation of seismic sections linking the Rankin Platform and Exmouth Plateau Arch suggests that the gently synclinal nature of the Cretaceous and Tertiary sequence persists at depth. Regional uplift and arching of the Exmouth Plateau area resulted in a synclinal appearance where previously the sediment surface had relatively normal seaward dips.

The Exmouth Plateau Arch consists of a broad anticlinal sequence of Cretaceous and Tertiary sediments overlying a faulted lower Mesozoic sequence. It becomes broader and simpler upwards: at the level of the Late Triassic, the crestal area is complex, whereas the Early Cretaceous sequence shows three culminations, and the Late Cretaceous and Cainozoic sequence has only a single structural high (Exon and Willcox, 1980).

The dominant fault orientation is northeast-southwest, bending around to a more easterly direction in the eastern part of the plateau. Seismic data suggest that the faults were active primarily in the Early and Middle Jurassic, with minor activity dating back to the late Palaeozoic and continuing until the late Mesozoic.

PEEDAMULLAH AND LAMBERT SHELVES

These are marginal to the Barrow and Dampier Sub-basins and have a northwestward-thickening veneer of Cretaceous and Cainozoic sediments resting on faulted Palaeozoic sediments and Precambrian rocks. The two areas are separated by the Cape Preston Arch and the Deepdale and Sholl Island Fault Systems. The Lambert Shelf contains very few Palaeozoic remnants beneath the Cretaceous, whereas the

Peedamullah Shelf contains extensive Permian, Carboniferous and Devonian sediments in northwesterly dipping fault blocks beneath the Cretaceous. The Peedamullah Shelf is generally bounded to the northwest by the Flinders Fault System. The limited data on or near the Lambert Shelf indicate that a graben, bounded shorewards by the Hauy Fault System, separates it from the Enderby Trend.

Thomas and Smith (1976) recognized the Ashburton Sub-basin between the Merlinleigh Sub-basin and Peedamullah Shelf, but this is here included largely within the latter. The Lambert Shelf was referred to as the Cape Preston Shelf and Pilbara Shelf by Thomas and Smith, but this terminology is avoided here because of possible confusion with the Cape Preston Arch and Pilbara Block.

DARLING FAULT

The Darling Fault is a major crustal fracture which had a profound influence on the Perth Basin (Playford and others, 1976). On YARINGA and AJANA, the Permian sequence (Nangetty Formation) crosses the gravity trace of the fault with no disruption, indicating that the fault did not move either during or after the Permian. On cursory examination, the Darling Fault cannot be traced north of the Wooramel River and instead appears to change direction to the northeast, so that it divides the Byro Sub-basin into two parts. However, the following structures all line up with a northward projection of the Darling Fault: the fault bounding the Devonian outlier near Munaballya Tank; the faults containing barite mineralization in the basal Lyons Group (south of Mount Sandiman homestead); the western side of the Weedarra Inlier; and lineaments in the Lyons Group between Pells Range and the Carrandibby Inlier. We suggest that the Darling Fault extends north along this line, and that it was last active between deposition of the Early Carboniferous Yindagindy Formation and the Late Carboniferous–Early Permian Lyons Group. No seismic data are available to test this hypothesis. Although lines cross the projection of the fault, they are not in areas where bedded sediments are thought to underlie the Lyons Group.

CHAPTER 12

Basin Evolution

This chapter summarizes the geological history of the Carnarvon Basin, and relates it to plate-tectonic models and the eustatic sea-level cycles of Vail and others (1977). The continental reconstructions proposed by Scotese and others (1979) and Smith and others (1981) are adopted for the Palaeozoic, and the reconstructions of Smith and others (1981), Parrish and Curtis (1982), and Parrish and others (1982) are used for the Mesozoic and Cainozoic. Sea-level curves are shown in Figure 125. Palaeogeographic reconstructions are shown on Plate 3.

PALAEOZOIC

SILURIAN

The oldest sediments which are clearly part of the Carnarvon Basin are the braided, fluvial to coastal red beds of the Tumblagooda Sandstone. Deposition of this sequence took place in an arid climate under temperate to tropical conditions. The thickness of the Tumblagooda Sandstone indicates that there was substantial hinterland relief, probably as a result of repeated major movements on the Darling Fault. Global sea levels were high during the Silurian (Fig. 125) and the presence of a thick continental to paralic sequence (with no deep-water facies) indicates that the depositional basin was relatively high topographically. There was also syndepositional movement on the Hardabut Fault (Playford and others, 1976) which may have been matched by movement on the Yandi Fault, but this did not lead to the emergence of the Northampton Block as a positive topographic feature. A drastic lessening in supply, probably due to cessation of movement on the Darling Fault, combined with a possible further eustatic rise in sea level, led to deposition in very stable conditions of the carbonate-evaporite sequence of the Dirk Hartog Formation. Rejuvenation of the hinterland area led to deposition of the Kopke Sandstone, and subsequent stabilization of the basin led to deposition of the Sweeney Mia Formation.

Veevers and others (1982) and Veevers (1984), following Veevers (1976) and Warris (1973), suggested that the Carnarvon Basin was a "failed arm" basin prior to the Late Carboniferous, and developed as a result of a period of rifting and divergence in the Cambrian in presently offshore, northern areas. The active tectonism indicated by the Silurian sequence supports this hypothesis, and suggests a further rifting episode along the west coast of Western Australia immediately prior to and/or during deposition of the Silurian sequence.

In the classification of Kingston and others (1983), the Silurian basin is best classified as a continental, interior-fracture basin, with minimal tectonic modification.

DEVONIAN

A marked eustatic drop in sea level may have occurred at the end of the Silurian (Fig. 125), resulting in emergence of the Carnarvon Basin and erosion of parts of the Silurian sequence. There is no definite evidence of tectonism accompanying this period of erosion, but the configuration of the basin changed. The Devonian sequence was deposited in a basin with a dominantly unconformable margin rather than a faulted margin, and the southern Carnarvon Basin may have been exposed. In Kingston and others' (1983) classification, the basin was an interior-sag basin. The unconformable margins reflect thermal cooling and lessening subsidence after the active rifting in the Silurian.

Sea level gradually rose in the Early and Middle Devonian and resulted in a marine transgression in the Givetian. It is not known how far south this transgression extended, but in the central Carnarvon Basin it overstepped the Silurian and extended on to the Precambrian craton. Residual weathered material was reworked into a basal sand, the Nannyarra Sandstone. Clear-water carbonate deposition occurred in the wake of the transgression, forming the Gneudna Formation. The sea was shallow, the basin was located

35—15

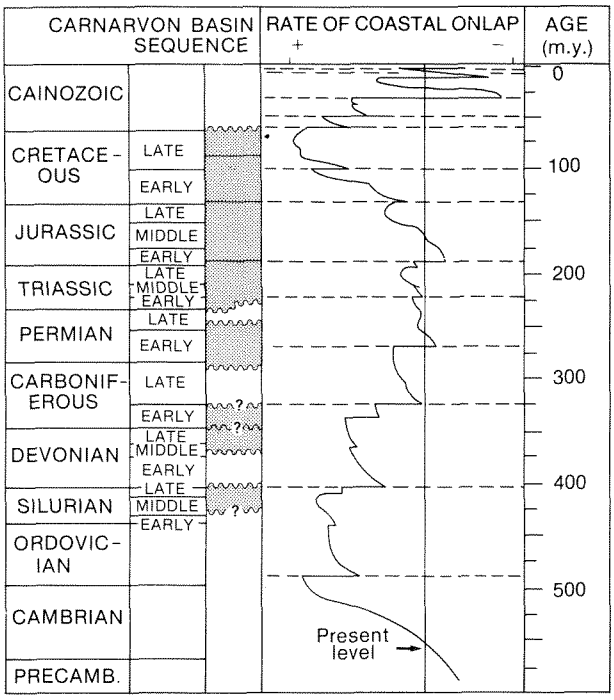

Figure 125. Second-order global cycles of relative sea-level change in Phanerozoic time. Modified from Vail and others (1977) and Loutit and Kennett (1981).

about 20°S to 25°S, and the shelf break may have been in the area of Pendock 1. Rejuvenation of the hinterland occurred in the Famennian presumably because of fault reactivation, although Devonian movement cannot be established for faults a short distance into the Precambrian hinterland, and the alluvial-fan and braided-fluvial sequences of the Munabia Sandstone and Willaraddie Formation prograded over the Gneudna Formation.

EARLY CARBONIFEROUS

The basin stabilized again in the latest Devonian–earliest Carboniferous and clear-water carbonate deposition returned, perhaps after a mild erosional break, forming the Moogooree Limestone in the Tournaisian. Vail and others did not show an abrupt sea-level fall at the end of the Devonian (Fig. 125), so tectonism may be involved if an unconformity separates the Devonian and Carboniferous sequences. The restricted fauna of the Moogooree Limestone and the presence of possible evaporitic nodules suggest abnormally high salinities, which may have been due to a rim developing on the basin to the west. Sea level fell abruptly in the early Visean (Fig. 125) and some faults marginal to the Carnarvon Basin were reactivated, resulting in alluvial-fan deposition. Although the only record of this depositional event is the Williambury Formation in the Williambury area, the presence of the shallow-marine, siliciclastic Quail Formation further west in the basin indicates that there must have been other areas of terrigenous influx into the basin. A slight sea-level rise later in the Visean, combined with a lessening of terrigenous input, led to nearshore, mixed-lithology deposition near the basin margin, forming the Yindagindy Formation.

During the Carboniferous, the Carnarvon Basin moved southwards from a position of 25°–30°S in the Visean to 60°–70°S in the Westphalian. The initial signs of the cooling of the climate are seen in the unnamed Lower Carboniferous sequence in the southern Carnarvon–northern Perth Basin, which may have been deposited by localized alpine glaciers debouching into a shallow sea or lake. There was a marked eustatic drop in sea level at the end of the Visean and this, combined with tectonic activity which folded the Devonian and Carboniferous sequence, exposed most of the Carnarvon Basin to subaerial erosion. The tectonic activity was in part the final stages of movement on the northern extension of the Darling Fault along the western sides of the Weedarra and Carrandibby Inliers. South of about 24°30′S (present latitude), the Devonian and Carboniferous sequence was entirely removed, and some Silurian sediments were eroded.

LATE CARBONIFEROUS–PERMIAN

By the Westphalian, the Carnarvon Basin was located at about 55°–70°S and the Late Carboniferous saw the onset of continental glaciation of the Precambrian hinterland. Basinal subsidence occurred, and a thick sequence of glacigene sediments, the Lyons Group, accumulated largely in marine environments. The Carnarvon and Perth Basins formed an elongate gulf, with a large expanse of open sea to the northwest (Johnstone, *in* Veevers, 1972). Severe glaciation ended in the Late Sakmarian and a widespread transgression occurred, possibly caused by post-glacial, eustatic, sea-level rise, during which the carbonates of the Callytharra Formation were deposited. The basin was locally arched, with shallower but not subaerial conditions between the Weedarra and Carrandibby Inliers. At the end of the Sakmarian a eustatic drop in sea level (possibly combined with isostatic uplift of the Western Australian margin after melting of most of the ice sheet) led to an emergence of the more easterly onshore part of the Carnarvon Basin. In the early Artinskian, karst topography developed on the Callytharra Formation in the arched area between the Weedarra and Carrandibby Inliers.

Continued subsidence as a result of the developing infrarift (or pre-breakup) setting of the Carnarvon Basin, combined with exposure of the hinterland after glaciation and increased surface runoff, resulted in progradation of the fluvial, deltaic and marine Wooramel Group in the mid-Artinskian. Some tectonism occurred during deposition and locally served to rejuvenate hinterland source areas. Continued subsidence and transgression through the Artinskian led to the expansion eastwards of the basin and the development of a broad marine shelf, on which the Byro and Kennedy Groups were deposited. Gross fining-upward cycles in the Byro Group, as for example from the Mallens Sandstone to the Bulgadoo Shale and from the Cundlego Formation to the Wandagee Formation, suggest that subsidence was periodic rather than gradual. The initial movements on the Kennedy Fault System probably took place during deposition of the Kennedy Group.

Although Veevers and others (1982, Fig. 9A) relate the Late Carboniferous–Permian sequence to a rift-valley basin, the apparent lack of major growth faulting and faulted margins suggests that the onshore Carnarvon Basin may be better related to an extra-arch basin setting.

It is not known how far Kennedy Group deposition extended into the Late Permian, but for the remainder of the Late Permian, the onshore Carnarvon Basin was emergent and subject to erosion. Because eustatic sea level was relatively stable after the Sakmarian, it is assumed that emergence of the basin was due to tectonic arching. The basin remained at relatively high latitudes.

Throughout the Palaeozoic, palaeocurrent data from fluvial deposits are dominantly northwestwards. This may indicate that, in the Palaeozoic, the Carnarvon Basin was an *en echelon* series of fault-controlled, northwestward-striking grabens with central drainage systems, which (prior to the Permian) obliquely abutted the Darling Fault and its northerly extensions. This orientation is not generally reflected in fault patterns except in the *en echelon* pattern along the western side of Kennedy Range.

The first recognized igneous activity in the Carnarvon Basin began in the Permian, with commencement of the intrusion of hypabyssal trachyte, phonolite and lamprophyre in the Edel 1 area. Igneous rocks of this age or composition are unknown elsewhere in the basin, and the relationship of the rocks to the tectonic development of the basin is unknown.

MESOZOIC

The Mesozoic development of the Carnarvon Basin from a plate-tectonic viewpoint has been discussed at length by many authors, such as Falvey and Mutter (1981), Veevers (1971, 1973), Veevers and Johnstone (1974), Veevers and Cotterill (1978), and Kopsen and McGann (1985).

LATEST PERMIAN–TRIASSIC

A marine transgression occurred in the Early Triassic in parts of the Perth, Carnarvon and Canning Basins, possibly caused by sinking of the continental margin, because Vail and others (1977) show no major eustatic changes in sea level during the Triassic (Fig. 125). The transgression only affected the northern Carnarvon Basin, and there were local seaways which had existed since the Late Permian. Within these seaways the Chinty Formation was deposited. In the wake of the transgression, the clays of the Locker Shale were deposited on a relatively shallow, quiet-water shelf. These conditions prevailed until the Middle Triassic in most areas, when deltaic complexes of the Mungaroo Formation prograded rapidly to the Exmouth Plateau area (Voss and McHattie, 1981), more than 300 km from the basin margin. Several fluvial systems were probably active, as fine-grained interdistributary areas can be recognized (Flinders Shoal 1). Deltaic progradation finished abruptly, with a marine transgression in the earliest Jurassic which reached the Exmouth Plateau in the Rhaetian and the Dampier Sub-basin in the Hettangian.

During the Triassic, a major reorientation of the Carnarvon Basin occurred. A pronounced, northeast-trending infrarift basin (as defined by Falvey and Mutter, 1978) developed, and the areas of Palaeozoic sedimentation in the onshore Carnarvon Basin underwent tectonic uplift. Erosion of the Palaeozoic sediments provided much of the terrigenous input to the northern Carnarvon Basin, and the present-day structural elements such as the Gascoyne Sub-basin and Wandagee Ridge began to develop.

Faulting and uplift along the southern margin of the Dampier Sub-basin developed the Enderby Trend, on which Palaeozoic sediments were stripped off prior to Triassic deposition. Rhyolitic volcanics were extruded along a trough between the Enderby Trend and the Lambert Shelf. Together, the tectonism and the volcanism suggest a small rift valley, of Late Permian–Early Triassic age on the southern margin of the Dampier Sub-basin.

JURASSIC

The major event which took place in the Jurassic was the breakup and onset of sea-floor spreading along the northwest margin of Australia at 155–160 Ma. This was preceded by major growth faulting around the margins of the Exmouth, Barrow and Dampier Sub-basins, with thick sedimentary sequences accumulating on the downthrown blocks. These sequences included marine siltstones and claystones (Dingo Claystone), alluvial fans (Learmonth Formation), fluvial sandstones (Legendre Formation), shallow-marine to coastal sandstones (Angel Formation) and turbiditic sandstones (Biggada and Dupuy Formations). In onshore areas the present-day sub-basins developed fully, with large-scale movements on major fault systems and, locally, very sharp uplift of small areas to form horsts of exposed basement, as in the Mia Mia and Woodleigh areas. The Gascoyne Sub-basin at this time was an elevated triangular horst complex which diverted sediment to the north and south. Only fine-grained sediment was deposited west of the horst complex, except along localized fault escarpments where alluvial-fan complexes (*e.g.*Learmonth Formation) formed. The coarse-grained detritus was diverted to the Dampier Sub-basin, where the fluvial-deltaic Legendre Formation was deposited, and south to the Perth Basin, where the Yarragadee Formation was deposited. Onshore, the age of alkali-picrite intrusives in the Wandagee area (160±10 Ma) suggest they are related to the peak in tectonic activity at breakup. Offshore, the "main unconformity" at the end of the Middle Jurassic in the Dampier Sub-basin (Crostella and Barter, 1980) marks the breakup event, as discussed by Falvey and Mutter (1981). Veenstra (1985) proposed that the Dampier Sub-basin initially was a Jurassic rift valley.

Subsidence and growth faulting continued after breakup. By the end of the Jurassic, the Gascoyne Sub-basin was stripped back to the Devonian-Carboniferous sequence in the north (except in small areas), and to the Silurian in the south.

CRETACEOUS

Deposition was continuous from the Jurassic into the Cretaceous, the first major event being the progradation of the Barrow Group deltaic complex over the marine Dingo Claystone and equivalents in the early Neocomian in the northern Carnarvon Basin. The source of the Barrow Group sands was the onshore Gascoyne Sub-basin. The succeeding Winning Group transgression resulted from a combination of eustatic sea-level rise (Fig. 125) and basin subsidence, and was accompanied in some areas by the extrusion of volcanics (as recognized in Yardie East 1) associated with the newly formed oceanic spreading centre. Unlike the Jurassic and Triassic sequences, the Winning Group transgression extended over much of the onshore Carnarvon Basin, reflecting peneplanation of the basin and more stable tectonic conditions.

In the Santonian, calcareous pelagic deposition replaced the siliceous pelagic deposition of the Winning Group, and the Toolonga Calcilutite formed on an extensive, low-energy, northwestward-deepening shelf. The advent of calcareous deposition was part of a worldwide event caused by changed oceanic-circulation patterns; following continental breakup. The change in deposition coincides with the highest eustatic sea levels (Fig. 125) recorded by Vail and others (1977). Carbonate deposition continued through the remainder of the Cretaceous.

CAINOZOIC

Carbonate deposition continued in the northern Carnarvon Basin throughout the Tertiary, in a series of depositional cycles described by Quilty (1977, 1980). These occurred in the Paleocene to Early Eocene, Middle to Late Eocene, Late Oligocene to Middle Miocene, and Pliocene to Holocene. They appear to be separated by periods of non-deposition rather than erosion, and they broadly correspond to the global cycles of Vail and others (1977). The onshore Carnarvon Basin was largely subject to erosion, with minor fluvial to nearshore marine siliciclastic deposition in the Middle and Late Eocene (Merlinleigh Sandstone), silcrete and laterite formation in the Oligocene and Miocene, and widespread but thin fluvial sheet-flood deposition in the Miocene (Pindilya Formation). Uplift of the coastal anticlines, due to reverse movement on pre-existing faults, commenced in the Eocene to Oligocene and continued through the Miocene into the Pliocene and Pleistocene. Minor reverse movement also occurred on parts of the Kennedy Fault System. This reverse movement was possibly a late-stage readjustment to the breakup and foundering of the Western Australian continental margin.

Reconstructions by Parrish and Curtis (1982) and Parrish and others (1982) show the northern Carnarvon Basin moving south from about 50°S in the Cenomanian to 60°–70°S in the Maastrichtian,

then back to about 50°S in the middle Eocene and about 30°S in the Middle Miocene (Plate 3.) Veevers and Cottrill (1978, Fig. 9) show similar Cretaceous palaeolatitudes. These figures are presumably based on the timing of the breakup between the southern Australian margin and Antarctica, which Falvey (1974) and Fraser and Tilbury (1979) placed at about 60 Ma. However, reinterpretation of magnetic-anomaly data by Cande and Mutter (1982) suggests that the time of breakup was instead 90–110 Ma. In this case, Australia may not have been as far south as suggested by Veevers and Cottrill (1978), Parrish and Curtis (1982), and Parrish and others (1982). Secondly, the globally high sea levels between the Cretaceous and Oligocene (Vail and others, 1977) imply that less ice was trapped in polar ice caps because of a warm climate. These two factors reconcile the Carnarvon Basin's apparent southerly position in the early–mid Tertiary with the tropical-subtropical climatic indicators of silcrete (Summerfield, 1983) and the faunal assemblages (briefly discussed by Quilty 1974.)

In the Pliocene and Quarternary, marine-carbonate deposition continued offshore, but onshore an increasingly arid climate led to widespread calcrete-duricrust formation in the Pliocene, and the Carnarvon Basin was essentially stable. During the Pleistocene, doming of the coastal anticlines continued, and several eustatic transgressive-regressive cycles occurred, with the formation of thick coastal-dune deposits in some areas. Little change has occurred in the Holocene over the onshore Carnarvon Basin other than the development of the Shark Bay and Exmouth Gulf areas as zones of extensive algal-dominated sedimentation.

CHAPTER 13

Economic Geology

PETROLEUM

INTRODUCTION

Petroleum exploration in the Carnarvon Basin began in 1924, but it was not until 1953 that an exploration well was drilled. This well, Rough Range 1, was drilled by WAPET on the Rough Range Anticline (Johnstone, 1979) and struck the first flowing oil (87 kL/day) in Australia's history. Although uncommercial, the discovery provided the impetus for continued exploration. WAPET had further success in 1964 when Barrow 1, the first well to be drilled on the Barrow Island Anticline, discovered oil in Neocomian and Tithonian sands at approximately 2000 m. It was completed and produced 155 kL/day of oil. Subsequent development showed that a larger accumulation existed in the Windalia Sand Member at about 620 m.

In 1963, Woodside was granted a large permit area over the North West Shelf, adjacent to the WAPET permit areas. After extensive geophysical investigations, Woodside drilled Legendre 1 in 1968. This was the first offshore well in Western Australian waters, and had a large (161 kL/day) but still uncommercial flow of oil. In 1971, the first of the Rankin Trend discoveries was made when North Rankin 1 discovered a large gas/condensate field. This was followed by the Goodwyn discoveries in Tidepole 1, Dockrell 1, Rankin 1, Egret 1 and Eaglehawk 1. At the southwestern end of the Rankin Trend, WAPET discovered the West Tryal Rocks and Gorgon Fields.

Other important discoveries are the Angel Field, in a horst complex south of the main Rankin Trend, and the Tubridgi Field, a shallow onshore accumulation in the basal Cretaceous.

Reserves in the producing and undeveloped fields are summarized in Table 4.

HYDROCARBON ACCUMULATIONS

A total of 285 exploratory wells had been drilled in the Carnarvon Basin (Table 5) to the end of 1984 (Elliott and others, 1985). The main hydrocarbon accumulations discovered are shown in Figure 126. The only producing hydrocarbon accumulations are Barrow Island Oil Field, which began production in 1967, and the North Rankin Gas Field, which commenced production in mid 1984. Several other accumulations are potentially commercial but as yet undeveloped (Table 4). These and numerous other indications in exploration wells have confirmed that the Carnarvon Basin has ample potential for the commercial exploitation of both gas and oil accumulations.

There are few surface indications of hydrocarbons in the Carnarvon Basin. Condit (1935) noted that there were occasional water bores which produced enough gas to be ignited at the well head, and that slurry from some other bores contained enough volatile material to be ignited. At the present time, Mauds Landing Bore commonly exhibits a faint oil slick on the artesian water, but no other such indicators are known.

Minor surface indicators occur on Barrow and Serrurier (Long) Islands. On Barrow Island above the Barrow Fault (Crank, 1973), there is local surface enrichment in sulphur, sulphate (gypsum) and organic matter. This has probably occurred by the microbial destruction of hydrocarbons (most likely gas) which escaped up the fault conduit. On the northern tip of Serrurier Island, in the intertidal part of the beach, sulphur is intermixed with lithified Quarternary beach rock. Considering the position of the outcrop, the softness of sulphur, and that the outcrop has lasted for more than 18 years (reported in 1957 by WAPET, visited by GSWA in 1975), we consider it unlikely that it originated other than by seepage of hydrocarbons.

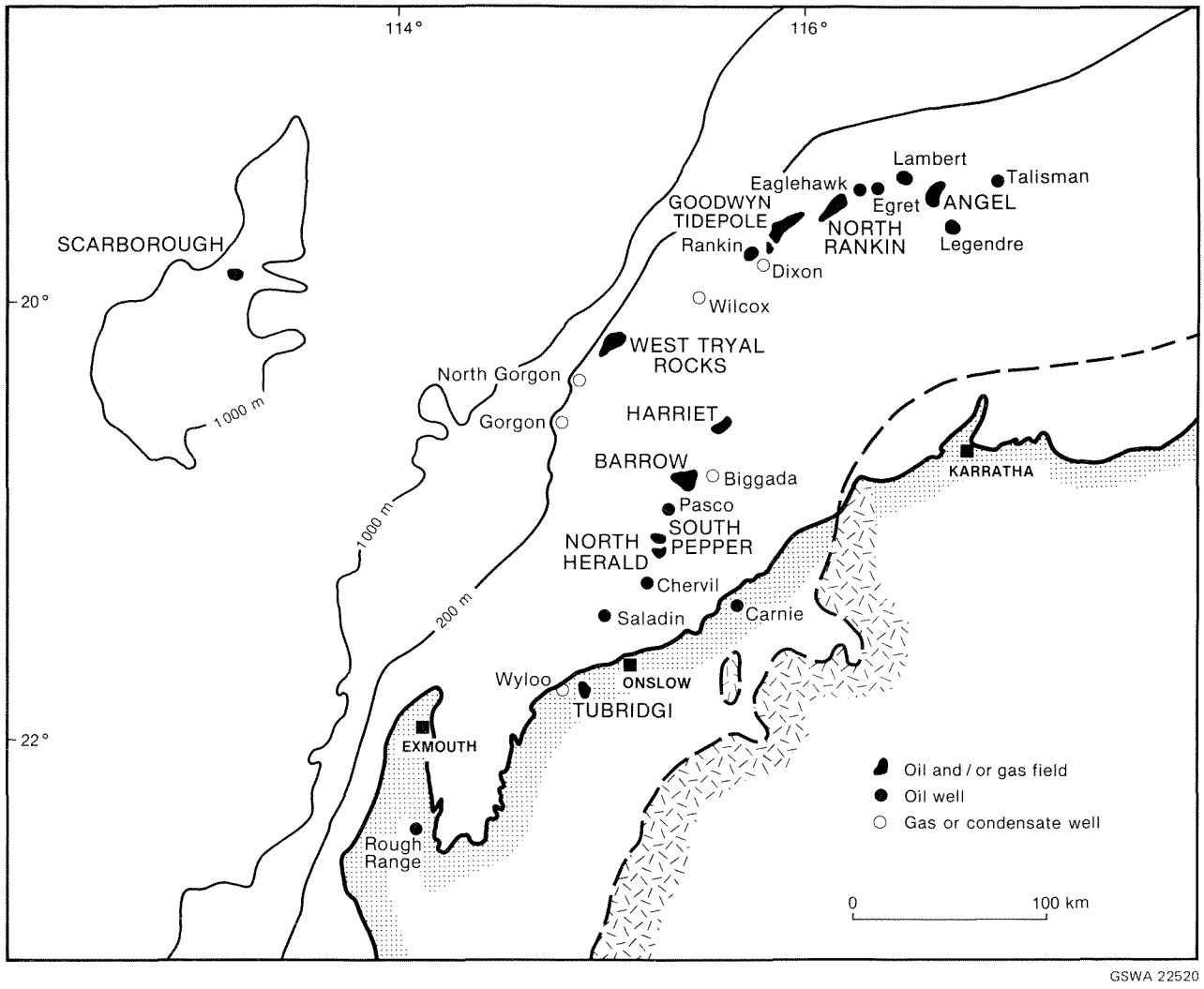

Figure 126. Known hydrocarbon accumulations in the Carnarvon Basin prior to 1984. Minor oil and gas shows not marked.

Barrow Island area

Barrow Island Oil Field: The Barrow Island Oil Field was discovered in 1964 and described by Crank (1973) and re-evaluated by Campbell and others (1984). The discovery well, Barrow 1, was drilled on the culmination of a surface anticline which, from gravity studies and limited seismic surveying, appeared to persist at depth. The field is complex, with at least 27 different reservoirs producing or holding oil and/or natural gas. These include the following:

(a) Two Upper Jurassic reservoirs in the Dupuy Formation between 2000 and 2100 m, producing mainly gas. These were the initial discovery reservoirs.

(b) Four Lower Cretaceous reservoirs in the Barrow Group between 1680 m and 2000 m, producing mainly gas, with some condensate from the upper sand.

(c) At least four reservoirs in the Muderong Shale between 650 and 850 m. The Windalia Sand Member is the principal oil producer; in addition the Mardie Greensand Member, "M3" and the Tunney Member also produce oil.

(d) The Gearle Siltstone between 400 and 500 m, which yields small amounts of oil from lenticular carbonate bodies.

The Windalia Sand Member is a very fine- to fine-grained glauconitic argillaceous sandstone which has a good porosity (28% average) but only a low permeability (average 5.7 mD). Because of this, primary recovery is low and it is not expected that much more than 25% of the oil will ever be recovered, even though secondary recovery is being employed. Numerous thin carbonate and shale beds restrict vertical migration through the sands, while intense fracturing restricts the effectiveness

of the water flood. Production rates are low, and if the accumulation had not been beneath an island, the field would not have been commercial.

Barrow Deep 1, Biggada 1 and Perentie 1 were drilled on Barrow Island between 1972 and 1976 to test the Jurassic section. All three encountered high-pressure gas and condensate in the Middle Jurassic sequence (Biggada Formation), but are not currently being produced. In Barrow Deep 1, the lowermost of three separate Middle Jurassic reservoirs had a net pay of 9.4 m, giving a calculated open-flow potential of 5.66 x 10^6 m^3/day. Biggada 1 had 11 m of net pay and Perentie 1 had 25 m of net pay with a maximum flow of 0.6 x 10^6 m^3/day.

A total of 685 wells had been drilled on Barrow Island by the end of 1984, and total production was 32.38 x 10^6 kL of oil and 2.92 x 10^9 m^3 of gas (Elliott and others, 1985).

South of Barrow Island: Several small oil and gas fields were discovered between Barrow Island and Onslow, beginning with South Pepper (1982) and continuing with Chervil (1983), South Chervil (1983), and North Herald (1983). Their economic viability had not been determined in mid 1984.

The accumulations are in oil columns less than 10 m thick in the Mardie Greensand Member and Barrow Group. Flow rates were up to 326 kL/day oil and 29 x 10^6 m^3/day gas. Williams and Poynton (1985) described the South Pepper accumulation in detail.

East of Barrow Island: In 1983, Harriet 1 and Bambra encounted good shows of hydrocarbons in the Barrow Group and, to a lesser extent, the Dingo Claystone. The Harriet field was under development in 1985.

Rankin Platform

North Rankin Gas Field: In 1971, North Rankin 1 intersected about 310 m of reservoir sandstone between 2687 and 3251 m (giving a gas column of more than 550 m) in the Triassic Mungaroo Formation, sealed by Upper Cretaceous shales. The trap configuration is a combination of four-way drape closure and fault seal, as the length of the hydrocarbon column exceeds the amount of anticlinal closure. Not all the faults are sealing, as gas occurs to the west of the main fault structure in North Rankin 4, and minor internal faulting within the main block results only in a 65 m difference in the gas-water contact across the field.

The Mungaroo Formation is an excellent reservoir, with porosity of the sands ranging between 17% and 25% and permeabilities between 500 and 1500 mD. Because of these parameters, high flow rates of 1.56 x 10^6 m^3/day of gas and 163 kL/day of condensate, through a 25 mm choke, have been achieved. Production from the North Rankin field commenced in August 1984. The field was described by Harris (1978), and its history and planned development were summarized by Agostini (1983).

Goodwyn Field: This is a Rankin Platform structure similar to the North Rankin field. The field covers a larger area than North Rankin, but the hydrocarbon column is only 348 m and the sand/shale ratio is poorer, resulting in smaller reserves. The sands have a good porosity ranging from 15% to 26% (average 18%), and permeabilities range beyond 2000 mD but are generally much less. Thick claystones in the Mungaroo Formation appear to act as intraformational seals, and there is a marked variation of gas-water contact throughout the field as well as a change in the proportion of associated condensate. Faulting is also an effective seal, as a large fault separates the main field from a southern block of the Tidepole structure. Goodwyn 3, in the southern block, intersected two hydrocarbon pools separated by water-wet sands. The upper pool is entirely gas but the lower pool contains 12 m of oil-bearing sands, a drill-stem test of which flowed 187 kL/day oil. In the main field, Goodwyn 6 flowed oil from at least two zones at up to 500 kL/day.

West Tryal Rocks: This is another typical Rankin Platform structure located nearly 100 km southwest of the main chain of discoveries. There are three main gas-bearing sand horizons which appear to be continuous across the field. Other thinner, less extensive gas-bearing beds also occur. Porosity ranges from 18% to 26%, and permeability from 45 to 2809 mD. Net pay in the Triassic section is 133 m. The maximum flow rate on drill-stem test was 411 x 10^3 m^3/day of gas and 35 kL/day condensate through a 12.5 mm choke. West Tryal Rocks 2 identified a separate accumulation below the main pool. Thin sand at the base of the overlying Cretaceous sequence were also gas charged, but appear to be part of the main gas pool.

A feature of the West Tryal Rocks accumulation is the presence of substantial quantities of inert gases. Most of the Rankin Platform accumulations are almost pure methane, but at West Tryal

Rocks the gas contains 9 to 12% carbon dioxide and 15 to 16% nitrogen. They vary inversely so that the volume of inert gas is consistently about 26%. The degrading effect of the inert gases on quality is offset by slight overpressuring of the gases beyond the normal hydrostatic gradient. The field also differs from other accumulations by the presence of low-salinity water beneath the gas column.

Gorgon, Central Gorgon and North Gorgon: The Gorgon structure was described by Campbell and Smith (1982). It is similar to the West Tryal Rocks structure. Drill-stem tests in Gorgon 1 produced gas at rates up to a maximum of 770 x 10^3m ^{3}/day gas from the Mungaroo Formation. The gas, like West Tryal Rocks, contains carbon dioxide (11%) and nitrogen (4%). North Gorgon 1, located midway between West Tryal Rocks and Gorgon 1, flowed gas at up to 974 x 10^3 m^3/day and condensate at up to 30 kL/day, with up to 19% carbon dioxide and 3% nitrogen. Central Gorgon 1, midway between Gorgon 1 and North Gorgon 1, flowed 1.07 x 10^3 m^3 gas and 15 kL condensate per day, with 18% carbon dioxide.

Other: Two other notable accumulations occur on the Rankin Trend in the Dockrell and Rankin structures. Both are primarily gas accumulations and were described by Crostella and Chaney (1978).

Dampier Sub-basin and Rankin Platform Flank

Tidepole: This is a horst block separated from the adjacent Goodwyn Field by a graben, and is structurally lower than it. The Mungaroo Formation is clay-dominated and draped by Cretaceous claystones. There is 402 m hydrocarbon column with seven hydrocarbon-bearing sands containing 79 m of net gas pay and 23 m of oil pay. The hydrocarbon-water contact is lower than in the Goodwyn Field, indicating that it is a separate accumulation.

Porosities in the sand range from 15% to 27% and, coupled with good permeabilities, result in high flow rates. A drill-stem test flowed 527 kL/day oil and 80 x 10^3 m^3/day gas on a 19 mm choke.

Angel Field: This field is located at the northern end of the Madeleine Trend in the Dampier Sub-basin. Only three wells have been drilled on it, and it appears to be smaller and less well defined than either North Rankin or Goodwyn. The reservoirs are Tithonian to early Neocomian sands, sealed by a thick Neocomian claystone sequence. The field is contained within a low-relief, gently anticlinal structure (with three high points) which appears to be full to spill point with gas. The gas column ranges from 91 m (82 m net) in Angel 1 to 52 m (33 m net) in Angel 2.

The Tithonian sequence is almost wholly sandy, with only thin, widely separated claystones which do not impede migration. Porosity in the sands is 17 to 22%, and permeability 150 to 727 mD (average 439 mD). The maximum drill-stem test flow rate was recorded in Angel 3, which flowed 385 x 10^3 m^3/day gas with 112 kL/day associated condensate through a 19 mm choke.

Other: After the discovery of the Barrow Island Field, the next important discovery was in Legendre 1. This was testing an analogue of the Barrow Island structure in the Dampier Sub-basin, and intersected a gross hydrocarbon column of 13 m containing a net oil pay of nearly 7 m. The Neocomian section was sand dominated; it had measured porosities of 16% to 23% and an average log-derived porosity of 17%. Permeability ranged from 6 mD to 74 mD on core samples, but the well flowed at up to 161 m^3 per day on a 19 mm choke with a gas-oil ratio of 1320. The accumulation is of significance as it lies in the migration path between the Angel accumulation and the basin flank. Given that the Angel structure appears to be full to spill point, the oil in Legendre could be the result of oil displaced from the Angel structure by later gas. This would upgrade the oil source potential of the beds sourcing the Angel structure.

Gas also migrated towards the basin flank. Hampton 1, drilled by Woodside on the flank of the Dampier Sub-basin, flowed 3410 m^3/day but the accumulation was too small to be commercial. So far it has proven difficult to find purely stratigraphic traps, but these undoubtedly occur and will become valid plays when the basin is better known.

Several structures are present on the southern flank of the Rankin Platform, on the Kendrew Terrace. Because of their lower elevation, erosion did not proceed to the same level as on the Rankin Platform, and a fuller stratigraphic column is generally preserved. They also contain more oil than accumulations on the main platform. The structures are the Lambert, Egret and Eaglehawk structures, and fuller details of each are available in Crostella and Chaney (1978) and Elliott and others (1985).

Other small accumulations have been found to give encouragement to exploration. Spar 1 tested a very low-relief structure and found a thin reservoir that produced at a maximum rate of 311 x 10^3 m^3 gas/day and 40 m^3 oil/day on drill-stem test.

Onshore

Rough Range: This was described by Johnstone (1979). Rough Range 1 was the first well in Australia to flow oil naturally to the surface, and flowed at the rate of 87 kL per day. However, eight follow-up wells were drilled unsuccessfully on what was believed to be the structure. Only the tenth, less than 200 m away from the discovery well, encountered oil. It is now believed that the structure contains no more than 45 000 kL oil in place. The oil was found in the Birdrong Sandstone and immediately raised this formation to prime-target status.

Tubridgi: The Tubridgi field is a relatively small gas accumulation in the Birdrong Sandstone and Mardie Greensand Member. Evaluation of the field was continuing in 1985. The gas may have migrated updip to the Peedamullah Shelf from either the Exmouth or Barrow Sub-basin.

Robe River: This occurrence was described by Thomas (1978), and is another indication of hydrocarbons migrating to the flank of the basin. While drilling a seismic shothole, a blowout of approximately 20 L of heavy brown oil occurred. This show is updip of the Barrow Island Field and could be either spill from it or oil which bypassed the structure. Thomas suggested that the area is a natural-migration path from the basin following the main line of sediment emplacement, the ancestral Robe River.

SOURCE-ROCK POTENTIAL

There is little quantitative data on the source-rock potenital of the Carnarvon Basin other than for the Jurassic and Cretaceous of the Barrow and Dampier Sub-basins. Limited quantitative studies were made by Cook and others (1985), Brikke (1982), Philp and others (1982), Alexander and others (1980), Philp and Gilbert (1980), Gould and Smith (1978) and Powell and McKirdy (1972). Qualitative assessments have been made of some other parts of the sequence (*e.g.* Crostella and Chaney, 1978; Knopsen and McGann, 1985; Percival and Cooney, 1985), but large areas are essentially unstudied. The most comprehensive study is that of Robertson Research International (1979).

Palaeozoic

There are no quantitative data on the source-rock potential of the Palaeozoic section. The Silurian sequence was deposited in oxidizing, arid conditions, and the source-rock potential is therefore low. Though the Dirk Hartog Formation is marine, it was apparently deposited in shallow, well-aerated water, making the preservation of carbon unlikely. No reefal developments are known. The only hydrocarbon show, to date, is a small gas show in the Tumblagooda Sandstone from the base of Wandagee 1 (Pudovskis, 1962).

The Gneudna Formation is the only probable source within the Devonian sequence. It is a shallow-marine deposit rich in organic debris, but the depositional environment appears to have been well oxygenated and most of the limestones appear to be poor in organic carbon. There is, however, ample evidence of algal structures, and the intersection in Pendock 1 suggests that basinal equivalents and possibly reefal sediments are present. These represent adequate to good source-rock potential.

The Carboniferous Moogooree Limestone and Yindagindy Formation are dominantly shallow-marine, moderate-energy deposits, and contain significant peritidal deposits with abundant algal-mat fabrics. In this setting, organic production may have been greater than destruction and good source-rock potential may exist.

Within the Permian sequence, the Callytharra Formation, Billidee Formation and Byro Group have some source-rock potential. The Callytharra Formation is mostly a moderate-depth to deep-water, quiet-water marine deposit with abundant organic debris. The restricted circulation (below wave base) and the depth of deposition would favour the preservation of organic matter. The Billidee Formation in part formed in a quiet-water, offshore-marine environment, conducive to the preservation of organic matter. Other parts of the unit formed in a swampy delta-plain setting, which could also give some source-rock potential. Much of the Byro Group formed in quiet, restricted-circulation, offshore conditions and thus may have source-rock potential.

Triassic

The Locker Shale was considered to have good source-rock potential by Crostella and Barter (1980). This was a qualitative assessment based on

environmental interpretation. Cook and Kantsler (1980) found abundant exinite, cuticle, and microplankton, and they assigned to the shale significant source potential. From analytical data, Brikke (1982) suggested that the Locker Shale was the source of Rankin Platform hydrocarbons and some Kendrew Terrace hydrocarbons but not Lewis Trough hydrocarbons. However, maceral studies in Sholl Island 1 and Onslow 1 showed that inertinite material is more abundant than vitrinite, and sapropelic macerals are less than 10%, making the formation only a moderate source for gas and a lesser source for oil.

The Mungaroo Formation is a variable deposit of a fluvial-dominated environment. Oil-prone macerals are scarce because of the dominance of terrigenous organisms, but from palynological analysis "the shales are rich in cuticular materials which are believed to be precursors of gas-condensate" (Crostella and Chaney, 1978, p. 18). Although a significant proportion of the shale macerals have no petroleum-generation potential, the organic carbon content of continenal shales is marginal to high, thereby upgrading the source-rock potential: mainly for gas. Marine parts of the Mungaroo Formation have a high organic carbon content, and the marine component suggests some oil or condensate potential. The overall source-rock potential of the Mungaroo Formation would vary markedly from area to area, depending on the sand content. Although some areas are sandy — hence the pessimistic potential shown by Crostella and Barter (1980, Fig. 18) — the sand content of the Mungaroo Formation overall is only about 35%. Cook and others (1985) presented an optimistic view of the source potential for oil of the Mungaroo Formation on the Exmouth Plateau.

Jurassic

The Dingo Claystone is found in all the Mesozoic sub-basins and is generally a fair gas source and minor oil source. The organic carbon content ranges from high to very high throughout (Robertson Research International, 1979). From maceral studies, Cook and Kantsler (1980) found that sapropelic material ranged from rare to abundant, and vitrinite occurred occasionally as local concentrations of thin stringers. They also noted that a considerable proportion of the macerals are inert and would contribute little or nothing to the petroleum potential of the source rocks. Robertson Research International (1979) found that vitrinite usually exceeded inertinite, though at times the two components were nearly equal. General trends are an overall improvement in source-rock quality both from Lower Jurassic to Upper Jurassic, and from south to north in the sub-basins. There is also a trend to more sapropelic material, from south to north. This might be explained by the evolution of the basin during this period: the connection to the open sea may have been to the north so that a larger contribution of marine material could be expected in this direction. Also, the Barrow Sub-basin appears always to have been a wide gentle basin while the Dampier Sub-basin, from Middle Jurassic onwards, was tectonically complex and may have had deep spots. These may have resulted in deposition taking place below the oxygenated surface waters, where bottom conditions may have enhanced the potential. Brikke (1982) considered that hydrocarbons in the Madeleine Trend and Lewis Trough (Dampier Sub-Basin) had a Jurassic origin, at least in part.

The siliciclastic formations of the Dampier Sub-basin appear to have good source potential. Pro-delta clays are rich in organic matter, both introduced by the fluvial system and locally generated. Though terrestrially derived, they are in large part deposited in marine conditions, so that a sapropelic contribution is possible in addition to the more gas-prone terrestrial component.

These source-rocks are widespread in the Mesozoic parts of the basin and have been buried to sufficient depth to have reached maturity. They are believed to be the source of the bulk of the oil so far found in the Carnarvon Basin. Exploration is far from complete, and the deeper parts of the basin may contain much better source rock than so far intersected. Grabens have proved to be major sites of high-grade source rock with both oil and gas potential (*e.g.* North Sea Graben).

Cretaceous

Moderate quality, oil-prone source rock of Cretaceous age has been identified in some wells, but by far the greatest part of the Cretaceous sequence appears to be gas prone, of modest quality, and at present largely immature (Brikke, 1982, Fig. 5). Humic (gas-prone) material exceeds oil-prone material in all maceral studies. Chemical analyses also indicate the Cretaceous sequence is gas prone rather than oil prone. A sapropelic component is present in varying amounts (Cook and Kantsler, 1980; Robertson Research, 1979). Over much of the Carnarvon Basin, the Cretaceous sequence is too shallow to be mature.

Cainozoic

The Cainozoic sequence is nowhere buried at sufficient depth to be near maturity, so its source-rock potential is negligible.

RESERVOIR POTENTIAL

Palaeozoic

Porosity and permeability are generally low to negligible in the Silurian, Devonian and Carboniferous sequences. The Silurian Tumblagooda Sandstone superficially appears to be a good reservoir, but diagenetic silica overgrowth and subsequent infilling of the remaining porosity by platy clays has resulted in virtually no intergranular porosity in much of the section. Some zones of good porosity (20%) and permeability (1000 mD or more) do occur locally, as in Yaringa 1. Joints are commonly sealed by silica, which reduces permeability on a larger scale.

Devonian and Carboniferous siliciclastic units are characterized by a high proportion of lithic grains, clay and, to a lesser extent, feldspar, all of which reduce porosity and permeability. In the few well intersections, they are described as tight.

In the Devonian Gneudna Formation, carbonate cement obliterated most intergranular porosity at an early stage. Dolomitization in part of the sequence may have produced porosity and permeability for early migrating hydrocarbons, but further dolomitization obliterated this porosity. The formation is widely distributed and requires detailed sedimentological and diagenetic study. A possible reefal development, the Point Maud Member, may have potential, but there are no other indications of reefal developments such as are present in the Canning Basin.

The Carboniferous Moogooree Limestone and Yindagindy Formation appear tight in outcrop, with no intragranular or intergranular porosity. However, in the subsurface, porosities of about 5% occur with a few zones up to 15%.

Sandstones within the Permian Wooramel and Byro Groups generally have low porosities and negligible permeabilities (*e.g.* in Quail 1, Kennedy Range 1, Onslow 1). However, they are not comprehensively sampled and in Kennedy Range 1, the Wandagee Formation in one interval was quite porous and permeable (Lehmann, 1967). This suggests some potential for reservoir development.

Triassic

The Locker Shale has minimal significance as a reservoir, but the Mungaroo Formation contains the giant North Rankin Gas Field and other hydrocarbon accumulations on the Rankin Trend. The Mungaroo Formation can contain large hydrocarbon columns because of its thickness, and because thick shales are present, intraformational seals and multiple pays are possible. The net to gross ratio varies markedly, and can make an accumulation economic (North Rankin) or uneconomic (North Tryal Rocks), but the average of 35% sand allows substantial accumulations.

The sands have been affected significantly by diagenetic quartz and siderite overgrowth, carbonate cementation, kaolinization and pyritization. However, subsequent leaching of the carbonate cement has enhanced porosity and permeability. Porosity ranges between 10 and 30%, with permeability up to 4000 mD. Porosity is reduced with depth, but this effect is generally overshadowed by leaching of cement (Crostella and Chaney, 1978). Thus, sands buried even deeper than 3000 m may have good reservoir parameters.

Jurassic

The Exmouth Sub-basin is bounded by large-amplitude faults which moved intermittently in the Jurassic, and shed large volumes of detritus into the basin, forming the Learmonth Formation. Though extensive stratigraphically, they are confined to a narrow zone about 15 km wide along the faults and thus form a limited objective. Where clean, coarse sands are developed, porosities around 20% are common and permeabilities range from 1000 to 7000 mD.

The Biggada Formation is a sequence of gas-bearing, Middle Jurassic sands below the main oil-producing horizons on Barrow Island. Porosities range between 16% and 27%, and permeabilities from 1 to 40 mD. The sands formed as turbidite flows, so they may have an extensive distribution in the basin centre. So far they are only known from the Barrow Island area.

The Dupuy Formation also has reservoir potential. Porosity within sandstone intervals is 15 to 20% and permeability 100 to 200 mD (Crank, 1973). A small amount of oil has been recovered from the unit on Barrow Island.

In the Dampier Sub-basin, the Legendre Formation has poor reservoir characteristics because of the depth of burial. Porosities of 7 to 15% and permeabilities of a few millidarcies, at the top of the unit in Rosemary 1, deteriorate to 5 to 10% porosity and about 0.1 mD permeability at the base. However, log porosities of more than 20% have been calculated in the Angel Field.

The overlying Angel Formation hosts the large gas accumulation of the Angel Field. It contains less claystone than the Legendre Formation, which increases the net to gross pay ratio within a structure, but reduces the possibility of multiple pays. Porosities are 17 to 20%, with permeability between 250 and 900 mD.

Cretaceous

The Cretaceous sequence has several potential reservoir units, the thickest of which is the deltaic Barrow Group. This occurs through most of the Barrow Sub-basin and Exmouth Plateau, and has a maximum known thickness of 1200 m south of Barrow Island. Sections consisting almost entirely of sand are known, but the average sand content is about 60%. The Barrow Group has been a prime exploration target in the Barrow Sub-basin and on the Exmouth Plateau, with porosities of 20–25% and permeabilities of hundreds of millidarcies.

Deltas also prograded into the Dampier Sub-basin in the Neocomian, and in Legendre 1, a thin oil column within them yielded 160 kL/day on test.

The basal transgressive sand of the Winning Group, the Birdrong Sandstone, extends through most of the Barrow, Exmouth, and Gascoyne Sub-basins and is usually a secondary objective. It is generally 20 to 30 m thick and locally about 60 m. Porosity and permeability are excellent, and small accumulations of oil occur at Rough Range and Barrow Island. South of Rough Range the unit has been efficiently flushed by groundwater.

The most important commercial Cretaceous reservoir is the Windalia Sand Member of the Muderong Shale, which accumulated on palaeo-highs and has a restricted distribution. The principal region is on Barrow Island, and most of the oil in the Barrow Island Oilfield is located in this unit. The porosity is 28%, but the permeability is low, giving low flow rates and poor recovery efficiency. The shallow depth to the member and its island location makes exploitation cheap at Barrow Island.

Oil saturation occurs in the Toolonga calcilutite in the North Rankin area but the unit is not a good reservoir. Calcareous zones in the Gearle Siltstone produce oil on Barrow Island, but they are not an exploration objective.

Cainozoic

The Cainozoic sequence is largely a prograding carbonate wedge, parts of which have excellent reservoir characteristics. Unfortunately, seals are absent, and to date no significant hydrocarbon accumulations have been located in these sediments.

SEALS

Palaeozoic

Within the Silurian sequence, portions of the Dirk Hartog and Sweeney Mia Formations are potentially excellent seals. Reservoir and source-rock development are greater problems than a seal.

The Gneudna Formation is the only potential Devonian seal. Laterally persistent fine-grained claystone and lime mudstone could act as seals. Coarser lithotypes appear to be tight in outcrop but in the subsurface, porosity may have been preserved, resulting in leaky seals. In the Lower Carboniferous sequence, the Moogooree Limestone is the only potential seal for similar reasons.

In the Permian sequence, the Lyons Group, Callytharra Formation, and fine-grained formations of the Byro Group could provide seals. In the Byro Group, this raises the possibility of source, reservoir, and seal all within the group; however, given the lateral persistence of Byro Group facies, traps would have to be structural rather than stratigraphic.

Triassic

The Locker Shale appears to be an excellent seal, but since it rests unconformably on older sediments and commonly has a basal sand, its potential is downgraded. The Mungaroo Formation is an important reservoir and within it there are intraformational seals. Multiple hydrocarbon/water contacts in some Rankin Platform structures (*e.g.* Goodwyn Field) demonstrate that these are effective.

Jurassic

The Dingo Claystone, is a satisfactory seal; and overpressuring in shale (Kyaw Nyein and others, 1977) confirms the efficiency of vertical migration barriers. An overpressured gas accumulation in the Biggada Formation below Barrow Island demonstrates the sealing ability of the Dingo Claystone.

Sandy Jurassic formations usually contain persistent interbedded shales which form intraformational seals.

Cretaceous

The Cretaceous Muderong Shale is the most important seal in the Carnarvon Basin. Where the Muderong Shale is not itself the seal (*e.g.* Windalia Sand Member horizon on Barrow Island) other Cretaceous sediments of similar lithology are effective. Large hydrocarbon columns have been discovered under very thin Muderong Shale seals. North Rankin Field has a column of nearly 600 m beneath only 15 m of Muderong Shale.

Intraformational reservoirs (usually calcareous horizons) are present within all the Upper Cretaceous formations (*e.g.* Barrow Island) but are not exploration targets.

Cainozoic

Fine-grained carbonate and argillaceous sediments occur in the Cainozoic, but in general the section has excellent vertical communication. No hydrocarbon accumulations with a Cainozoic seal have been recognized in the Carnarvon Basin.

HYDROCARBON TRAPS

The Carnarvon Basin has always been an epicontinental area with a rigid crust, and tectonism has been tensional rather than compressional. Most faults are normal, but some appear to be wrench faults with locally generated compression. Thus, most anticlinal features are due to drape over underlying horsts (*e.g.* North Rankin) rather than compressional folds. Individual fault blocks, sealed by juxtaposition of reservoir and seal (or fault plane), must also be present. Stratigraphic traps will be increasingly sought as knowledge of the basin increases. Small, isolated, limestone horizons have produced oil on Barrow Island, but are too small to be commercial on their own.

The Rankin Platform was severely disrupted by Middle Jurassic tectonism into a large number of tilted fault blocks. A series of *en echelon* horsts was created, forming the prolific traps of the trend. Two factors enhanced the traps. Firstly, the dipping Triassic sediments contained intraformational seals and if the lateral faults sealed and the reservoir did not subcrop, a large trap resulted. Secondly, where intraformational seals were absent, draping of Cretaceous seals over the upstanding Triassic resulted in anticlinal closure. Apart from the relative elevation of the horst block, differential compaction of sediments over and adjacent to the horsts amplified the closure. When initially drilled, the seismic quality was too poor to resolve the sub-unconformity faulting and the platform was drilled on the anticlinal closure. The great magnitude of the faulting (over 2000 m) was only realized after drilling: as well as a series of crestal horsts which may contain gas (West Tryal Rocks, North Rankin), there is a series of flanking, lower terraces sometimes charged with oil (Tidepole, Eaglehawk). Oil migrating from mature source-rock might be trapped in the lower fault blocks while gas is free to migrate to the higher blocks. Examples of these structures were given by Meath and Bird (1976), Kaye and others (1972) and Crostella and Chaney (1978).

Several mid-basinal high trends occur in the Dampier Sub-basin, each with a number of separate culminations. As Jurassic and Cretaceous sands are restricted to the northern part of the sub-basin, the best reservoirs are on the northeastern end of the trends. For example, along the Madeleine Trend reservoirs are absent at Withnell and improve towards Angel, which is at the highest point of the trend and contains a gas accumulation. Similarly, sands improve to the north along the Legendre Trend, and a small oil accumulation occurs at Legendre, almost the highest point. The Barrow Island field occurs on the highest point of the Barrow Island Arch in the Barrow Sub-basin.

The faulted southeastern margins of the Mesozoic sub-basins also contain numerous fault blocks and horsts, and may be suitable exploration targets, being the first up-flank structures from mature source-rock. Hampton 1 located a small gas accumulation, but this trend has not proved prolific. The Tubridgi Field can also be placed in this category. Basin-margin stratigraphic traps must occur in the Mesozoic sequence. The Robe River accumulation is an indication that oil has moved in this manner, as is the Tubridgi Field, although it is not a stratigraphic trap.

Cainozoic reversal of movement over major faults has resulted in a series of anticlines, formed as drapes over the uplifted fault blocks, along the coastal region from Cape Range to Shark Bay. Rough Range 1 located a small oil accumulation, and the Cape Range structure contains some gas, but the other anticlines which were drilled have been dry. Some of the smaller anticlines remain untested. Although they are relatively young structures, their positions over deep faults could allow charging of the structures from deeper source rocks.

COAL

The only portion of the sequence in the Carnarvon Basin which appears prospective for coal is the Wooramel Group. This is the only unit in which there are sizeable delta-plain or coastal-swamp deposits, conducive to the development of coal. While coastal-swamp deposits occur in the Cretaceous Nanutarra Formation and Yarraloola Conglomerate, the sequence has never been buried deeper than at present so that coal seams are unlikely.

Thin seams of coal are known from the Wooramel Group in the Wandagee area and in the southern Byro Plains area. Exploration programs, including broadly spaced reconnaissance drilling, have been carried out by several companies in both areas, without commercial success. Coal was first intersected in the Wandagee area in Quail 1, in the Billidee Formation and Moogooloo Sandstone at depths of at least 200 m. Follow-up drilling indicated that the coal seams, which are of coking quality but less than 1 m thick, do not thicken markedly in any direction and are shallowest near Quail 1 (The Broken Hill Proprietary Company Ltd, 1976a; Devlin, 1983). Areas to the southeast (beneath the Cretaceous), to the east (beneath the Coyrie Formation near Gooch Range) and to the north (near the Lyndon River on Mia Mia Station) remain untested.

In the Byro Sub-basin, coal was recovered from BMR 8 (Mount Madeline) and some seismic-survey shotholes. Subsequent exploration has centred on the Keogh Formation, with the Moogooloo Sandstone as a secondary target, in the area between the Murchison River and the Carrandibby Inlier. There has been extensive drilling by several companies (note the scatter of holes on Plate 2) but no significant coal intersections have been found. Delta-plain and delta-front deposits occur in the Wooramel Group in adjacent outcrop areas, but no detailed integrated environmental analysis has been made of the group as a whole in the Byro Sub-basin.

The principal problem with coal exploration in the Carnarvon Basin is the probable depth at which coal might be present. In areas where the Wooramel Group outcrops, dips are normally between 10° and 20°, meaning that any coal seams (and although none are known in outcrop, this could be because of weathering) will reach an unminable depth over a relatively short distance laterally. Away from outcrop, the facies present and the depth of burial are commonly uncertain.

METALLIC AND INDUSTRIAL MINERALS

(P. H. Harrison)

INTRODUCTION

The considerable volume of mineral-exploration data which is held in Mines Department files was reviewed in the light of a number of models of mineralization by Harrison (1985). The following sections are a summary of that review.

BASE-METAL POTENTIAL

Models for the genesis of sediment-hosted base-metal sulphide deposits invoke the formation of metal-rich brines within the sedimentary pile. Carpenter (1978) suggested that most brines of commercial interest originate as interstitial fluids in halite-rich rocks. Jackson and Beales (1967) suggested that brines are expressed from large thicknesses of sediment during compaction, desorbing and dissolving base-metals ions which were previously absorbed during sedimentation. Such brines may then migrate, in a manner similar to hydrocarbons, to sites of deposition.

Thick evaporite sequences are present in the Silurian succession of the Carnarvon Basin and thick argillaceous sequences, including evaporite-bearing rocks, are known from several sequences.

The presence of distal volcanism may be significant in the generation of sedimentary base-metal deposits. Volcanic or shallow-hypabyssal rocks were intersected in Edel 1 (Permian-Triassic), Enderby 1 (Permian), and Yardie East 1 (Neocomian). The Lower Cretaceous sequence contains extensive bentonitic siltstones, and a probable tuffaceous (horizon containing shards of devitrified glass and angular-feldspar phenocrysts) occurs in the Gearle Siltstone sequence of the Giralia Anticline.

Faulting during periods of tectonism could have provided a "plumbing system" for the migration of mineralizing brines which may have been generated within the basin. Veins carrying barite, galena, and sphalerite, cut both Precambrian basement and the overlying Lyons Group approximately 10 km south of Mount Sandiman homestead, and indicate that such brines were developed in Late Carboniferous, or later, times.

Indirect evidence for a Silurian mineralizing event is seen in the Northampton Block. Epigenetic lead-zinc mineralization occurs in veins parallel to dolerite dykes. Hydrothermal alteration associated with these veins has recently been dated at 434 Ma years (J. Blockley, pers. comm.).

Michael and Groves (1977) suggested that brines formed by the intersection of Silurian meteoric water with basement metasedimentary rocks, and the resulting mineralized brines flowed preferentially along the unconformity between the basement and the Tumblagooda Sandstone.

Several areas of anomalous geothermal gradient are related to faults and others basement structures (Moors, 1980). A number of faults, for example the Rough Range Fault, formed major growth faults during the Jurassic, and remained active through to the Cretaceous. They thus could have formed suitable conduits for mineralized brines during Cretaceous times. The present anomalous high heat flow, associated with the fault, may well represent the waning phase of a former hydrothermal system.

Carbonate-hosted lead-zinc deposits

Mississippi Valley-type epigenetic mineralization may occur in carbonate sequences in palaeokarstic weathering systems beneath unconformities and in fault and breccia zones. Mineralization is often in reef or fore-reef breccia sequences, commonly developed on the flanks of basement ridges or close to basement edges. There is a frequent association with (local) dolomitization and silicification of the host-carbonate sequence. Unconformities may be significant both in producing suitable sites for deposition (through karstification), and in providing channelways and traps for mineralizing brines.

These programs focused on three main carbonate sequences. Each carbonate sequence may have undergone karstic weathering and the two older sequences were subject to pre-Permian tectonism which could have acted as a "plumbing system" for the mineralizing brines.

Gneudna Formation: The majority of the carbonates are limestone, however, local areas of dolomite occur and dolomitization becomes more pervasive in the upper part of the formation. The bulk of the formation was probably deposited in an epeiric sea. No definite reef developments are known although platform facies may be developed in Pendock 1.

In outcrop, the Gneudna Formation is mostly overlain by Willaraddie Formation or Munabia Sandstone, which are relatively poor traps for mineralizing fluids. However, in the southern part of the outcrop area, locally further north, and in places in the subsurface, the formation is overlain by the Lyons Group which may have formed better traps. In much of the central and northern parts of the basin the Gneudna Formation is overlain by Cretaceous rocks.

Diamond drilling carried out by Aquitaine, in one area with a strong geochemical lead anomaly in soil (to 3200 ppm) near Ebra Bore, located minor galena mineralization in fractured, vuggy dolomite, associated with minor organic matter, possibly bitumen. Grab samples assayed up to 6500 ppm Pb and 1850 ppm Zn, while a 4m interval assayed 4000 Pb and 219 ppm Zn.

International Nickel Australia Ltd (Inco) located possible gossanous material assaying over 1% Pb northeast of Woodcock Bore. Infill sampling of the zone showed that it was of limited extent.

Drilling completed by various companies during uranium exploration located pyrite mineralization in several places within the Gneudna Formation. A number of base-metal anomalies have also been reported.

Exploration has shown that mineralizing brines passed through the Gneudna Formation. There is thus a reasonable possibility that significant mineralization could be developed in suitable depositional sites. Such sites could be present in the areas where the Gneudna is unconformably overlain by the Lyons Group; in zones of porosity associated with pre-Permian faulting; or with possible reef developments.

Moogooree Limestone: The bulk of the unit consists of fossiliferous and oolitic limestone which is commonly dolomitized. Some siliciclastic rocks are present near the base of the sequence.

The Moogooree Limestone contains a high proportion of algal material and chemical precipitates, perhaps as a result of hypersaline conditions (Lavaring, 1979; Radke and Nicoll, 1981). Corals are present, especially in western and southernmost outcrops, and brachiopod coquinas occur locally.

Throughout much of the outcrop area the Moogooree Limestone is conformably overlain by sandstone of the Williambury Formation. In the southern 11 km of outcrop, however, it is unconformably overlain by the Lyons Group, which potentially forms a much better trap for mineralizing fluids.

Aquitaine, following the location of rock chips assaying 1900 ppm Pb and 1% Zn, drilled two diamond-drill holes in the southern part of the sequence. Assays up to 1.1% Zn and 1400 ppm Pb, over one metre, were obtained from a porous oolitic limestone. Individual grab samples assayed up to 2.2% Zn.

Inco carried out a helicopter survey of the entire strike length of the Moogooree Limestone. This showed that base-metal anomalies were essentially restricted to that portion of the limestone which is unconformably overlain by Permian rocks. North of the area previously examined by Aquitaine, a gossan assaying 1.27% Pb, 2020 ppm Zn and 6600 ppm Ba was located. Gully samples assaying up to 2563 ppm Pb were also obtained.

A program of detailed, grid-controlled geological mapping, soil sampling, and induced polarization surveying located a number of gossan outcrops. Some of these contain hemimorphite. Several strongly anomalous lead and zinc soil anomalies were outlined, assaying up to 775 ppm Pb and 670 ppm Zn. The induced polarization survey results were interpreted as indicating several potential sulphide conductors. An attempt was made to drill these anomalies; however, as a result of technical problems none of the holes reached their target depth. No base-metal mineralization was intersected although one hole drilled a gossan zone assaying up to 1.3% Pb.

This work suggests considerable potential for mineralization where the Moogooree Limestone is overlain by the Lyons Group. The anomalous sections outlined in the southern 11 km of the outcrop are largely untested, and further potential could be present elsewhere to the west.

There is evidence of pre-Permian faulting, particularly in the vicinity of Williambury homestead, and associated breccia zones are possible target zones for mineralization.

Callytharra Formation: It has been the subject of reconnaissance exploration for Mississippi Valley-type mineralization by a number of groups. During regional exploration programs the majority of the strike length has been flown in a search for gossans. Although a number of ferruginous units were located, only very slightly anomalous base-metal values were reported; *e.g.* north of Mount Sandiman woolshed (where they were interpreted as resulting from manganese scavenging) and northeast of Bidgemia homestead. Textures in the gossans indicate that they are derived from pyrite and marcasite, with no evidence of base-metal sulphides.

As a result of this sampling it was concluded that the main Permian mineralizing event preceded the deposition of the Callytharra Formation.

Stratiform copper mineralization

Annels (1984) suggested that the sediments of the Zambian Copper Belt formed as an infilling of an ancient aulacogen, with metals being derived from the seepage of magmatically enriched hydrothermal solutions along Precambrian rift systems and associated fractures. Harrison (1985) suggested that mineral deposits of this type could be present within the rocks of the Silurian Kalbarri Group, as they may have been deposited in an aulacogen similar to that of the Copper Belt. The overall relationships of the constituent formations are not dissimilar to those described from many 'red-bed' copper deposits.

The provenance of the Tumblagooda Sandstone was from the southeast (Hocking, 1981), and clasts of Archaean and Proterozoic rocks, including Coomberdale Chert from the Moora Group, are present. Sediments could also have been derived from the Yandanooka Group, in which copper mineralization is present in the Arrowsmith Sandstone and Arrino Siltstone; and from the Billeranga Group, in which copper mineralization is known in the remnants of the previously more extensive Morawa Lavas.

There may be potential for copper mineralization in coastal sabkhas of the Dirk Hartog Formation and Sweeney Mia Formation. These are probably developed in the area between the Murchison and Wooramel Rivers. Possible indications of sulphide mineralization are given by the presence of pyrite in the Dirk Hartog Formation in Tamala 1 and in the Sweeney Mia Formation in Yaringa 1 and Hamelin Pool 2. Pyrite was also noted in possible Silurian red beds which were intersected in coal-exploration bores near Meadow homestead. None of these intersections appear to have been assayed for base-metals or associated indicator trace elements.

These potential target sequences are not exposed but occur at a shallow depth in much of the area and thus could represent a potential exploration target.

Stratiform, shale-hosted, lead-zinc and copper-lead (silver) deposits

Two sequences in the Carnarvon Basin warrant exploration for mineralization of this type.

Shales of the Byro Group: The black-shale facies of the "fine-grained facies association" may have potential for stratiform base-metal mineralization, particularly in the Bulgadoo and Quinnanie Shales, but also in the Baker Formation and Wandagee Formation.

The black-shale facies contains significant amounts of pyrite, as disseminations and fine bands, and, in outcrop, secondary gypsum. Phosphate may be present (up to 1.25% has been recorded) indicating slow deposition.

If mineralized brines were debouched into the basin during sedimentation, or if they saturated the sediments soon after deposition, then conditions would have been ideal for the formation of base-metal mineralization. The presence of barite-galena-sphalerite veins cutting the basal Lyons Group in the Mount Sandiman area was discussed above. These indicate that at least some mineralizing fluids were generated, during or after Late Carboniferous times, and suggest that further evaluation of the Byro Group could be justified.

The shale sequences are seen mainly in river and creek sections. Elsewhere, superficial deposits effectively blanket the sequence. The sequence has been intersected in several drill holes put down for phosphate or potash exploration. Although considerable quantities of pyrite have frequently been logged, no assays for base metals or indicator elements have been reported to the Mines Department.

Bentonitic and radiolarian shales of the Winning Group: The setting for Winning Group deposition shows some geological and tectonic similarities to the present Red Sea rift. Possible analogues of the presently forming mineral deposits in the brine pools of the Red Sea could be present in the Winning Group.

The group is unusual in that pelagic-type sediments were deposited at less than 1000 m depth.

Several of the shale and siltstone sequences are potential hosts for base-metal mineralization.

Muderong Shale: In the Giralia Anticline, drill intersections are frequently found to be bentonitic and to contain pyrite as nodules, stringers, and fine beds. Pyrite has also been reported as a cement in sandy layers. Thin beds of fine-grained dolomitized limestone have been recorded.

Windalia Radiolarite: This is best described as a radiolarian siltstone. Siderite-cemented interbeds occur locally. Carbonaceous sequences are present in places. In the Giralia Anticline, drilling has shown that these occur as local thickenings which may represent deepening areas of the sedimentary basin.

In bores around the Shark Bay area, 70 cm thick beds of black, conchoidally fracturing chert are present in the sequence. Pyrite is common as disseminated nodules and fine interbeds.

The unusually high silica content may result from fumarolic and hydrothermal activity associated with the development, offshore, of the volcanic spreading centre (Harrison, 1985). Sediments in the Red Sea brine-pools are also characterized by a high proportion of silica, together with sulphides, iron oxides and carbonate.

Gearle Siltstone: This is a dark, grey-brown to black, bentonitic siltstone grading into silty claystone. Radiolarian-rich siltstones are present near the base of the formation.

A feature of the siltstone is the presence, near the middle of the sequence, of a number of beds of stratiform, sedimentary barite, up to 40 cm in thickness. Drilling suggests that these are lenticular. In outcrop, nodules of barite are scattered across the surface. The Gearle Siltstone is commonly pyritic. Stratiform pyrite is known from a number of sections (including some of the barite-rich intervals) while disseminated pyrite (together with nodules) and tube-like aggregates of marcasite-pyrite are also common.

The Winning Group has been subject to a number of low-key exploration programs for phosphate, bentonite, and barite. However, only one exploration program (by Inco in 1978–79) for base metals has been reported to the Mines Department. This centred on the Giralia Anticline. Exploration started after the identification of anomalous silver values in sulphide nodules and microgossans in the Gearle Siltstone near the occurrences of bedded barite, and consisted of geological mapping, stream and rock-chip sampling, auger and air-core drilling and trial input-EM surveys.

Several highly anomalous silver values, up to 352 ppm, occurred in sulphide and goethite nodules and microgossan chips. Values over 30 ppm Ag were mainly restricted to the upper part of the Windalia Radiolorite and the lower part of the Gearle Siltstone in the north of the structure. A number of anomalous zinc values in excess of 1000 ppm were also recorded from these surface samples, with values to 1250 ppm Zn and 120 ppm Pb. Microgossan chips collected from water-bore sludge assayed over 2% Zn. Mineragraphic examination suggested the presence of sphalerite textures in this material. There is some possibility that these chips could have been derived from the

Permian Byro Group (which underlies the Cretaceous in much of the Giralia Anticline) but this was considered to be unlikely in view of the oxidized nature of the samples.

No significant base-metal or silver values were obtained in the deep-drilling program and it was concluded that any mineralization was too sparsely distributed to be economically significant. The presence of saline groundwater and carbonaecous horizons caused continuous activity on all EM channels.

The presence of anomalous silver and base-metal values together with base-metal microgossans is considered to provide further evidence of the metalliferous potential of the Winning Group sequence, although there is a strong possibility that any significant mineralization could be basinward of the Giralia area, or even offshore and thus outside the range of economic exploration.

The anomalous heat flow associated with the Rough Range Fault, to the northwest of the Giralia Anticline was noted above. A second area of anomalous heat flow (Moors, 1980) in the area of Gnaraloo 1 and Chargoo 1, possibly resulting from the movement of formational fluids associated with a horst block in the Palaeozoic "basement" in this area. The Winning Group sediments, over and adjacent to both of these structures, may well have significant potential for "sedimentary exhalative" base-metal mineralization. Another area of anomalous heat flow in the Rover River area (Moors, 1980) should also be evaluated.

ALKALI PICRITES AND DIAMONDS

Reconnaissance exploration for kimberlites commenced in the Carnarvon Basin in the mid 1970s and culminated in the discovery by CRA Exploration Pty Ltd, in 1978, of alkali-picrite dykes and pipes in the Wandagee area. The pipes were found as a result of sampling stream gravel for indicator minerals. The work located kimberlitic pyrope garnet and chrome diopside. Further details of the discovery are given by Atkinson and others (1983, 1984) and Jaques and others (1986). The area of the pipes and dykes is referred to as the Wandagee Province and was described in Chapter 3.

The province consists of 16 separate pipes and dykes of alkali picrite in an elongate north–south zone some 50 km long. The cluster is situated in the densely faulted, westernmost part of the Merlinleigh Sub-basin, immediately east of where the Wandagee Fault has its greatest throw and changes its direction. Emplacement of the alkali picrites is probably due to tensional crustal fracturing during separation of the Australian and Indian continental plates.

The apparent relationship of the alkali picrites to major fault systems raises interesting possibilities for further exploration. Several other major faults between major horsts and grabens *(e.g.* Marilla Fault, Ajana Fault System, and Darling Fault) probably represent major tensional crustal fractures and are therefore potential sites for alkali-picrite intrusion. In many places, the faults are covered by younger sediments. The experience of CRA indicates that detailed airborne-magnetic surveys can locate buried alkali-picrite pipes beneath relatively thin cover.

Following CRA's initial successes there have been few indications giving further encouragement. Only a few very small possible additional (non-diamondiferous) dykes and plugs of alkali-picrite have been located, although several unexplained occurrences of kimberlitic indicator minerals have been reported (Harrison, 1985).

Stockdale Prospecting reported the presence of trains of indicator minerals which appear to be derived from Cretaceous sediments. As the Wandagee alkali picrites are Jurassic, it may be assumed that a considerable volume of kimberlitic material was eroded prior to the Cretaceous (Fig. 127). Some debris may have been incorporated in shoreline heavy-mineral concentrations in the Birdrong Sandstone. It it considered that these should be examined further for possible alluvial-diamond concentrations.

URANIUM EXPLORATION

Harrison (1985) concluded that the area with most potential for uranium mineralization was restricted to the central part of the basin, approximately between the Gascoyne River and the Cane River. Within this area the potential source rocks of the Gascoyne Province include extensive areas of 'S' type granitoids and associated pegmatites. These were probably derived by anatexis from metasediments and contain highly anomalous amounts of uranium. There has also been some concentration of uranium in valley calcretes which have subsequently been eroded into terraces during a recent rejuvenation.

Of the six types of deposits which Dahlkamp (1978) regards as having potential economic significance, the sandstone types are most likely to occur within the Carnarvon Basin. Dahlkamp pointed out that while individual deposits of this

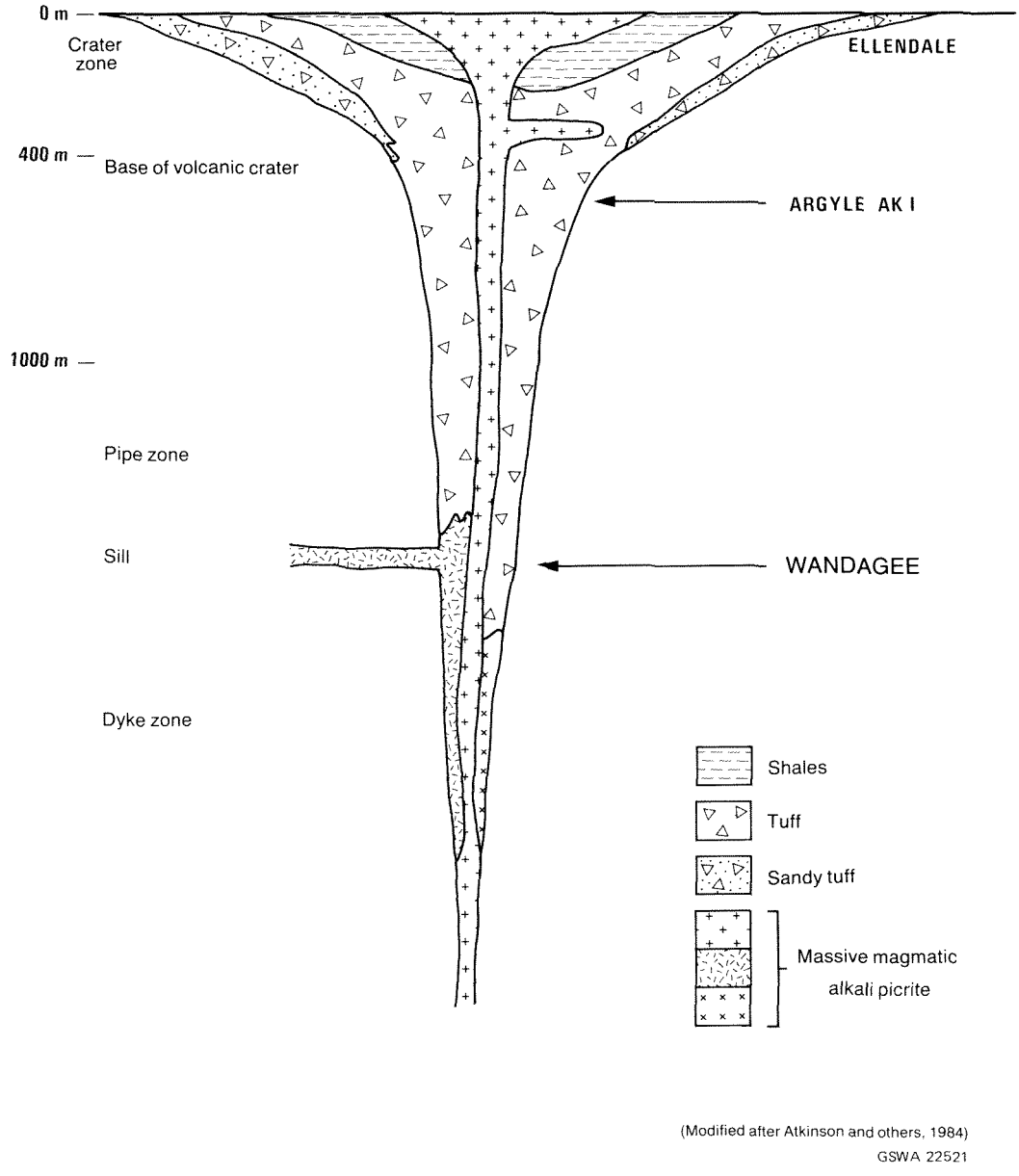

Figure 127. Cross-section of a Western Australian "kimberlitic" pipe, after Atkinson and others (1984).

type may be small, the potential for a district as a whole is considerable. 95% of uranium reserves in the United States, for example, are in deposits of the sandstone type.

Roll-front deposits

The roll-front type of deposit has been the target for most of the uranium exploration conducted in the basin. Several occurrences of uranium mineralization have been discovered, and at least one is potentially economic. This was described by Valsardieu and others (1981). It is located near Nanyingee* Hill and occurs within fluvial and deltaic portions of the Birdrong Sandstone or Nanutarra Formation, palaeochannels incised into basement granitoids and "sealed" by siltstones of the Muderong Shale. The deposit, which is associated with a redox front, is in many ways typical of the roll-front style of mineralization (Fig. 128). One unusual feature is the presence of brannerite — (U Ca Fe Th) (Ti Fe)$_2$O$_6$ — together with minor rutile and ilmenite, in the reduced zone. The preservation of brannerite suggests that the source of the uranium must be of very local origin, probably from granitoids which outcrop just southeast of the mineralization.

Fairly extensive exploration in the Cretaceous sequence, in the northern part of the basin, has resulted in the discovery of numerous palaeochannels and several occurrences of mineralization associated with redox fronts.

* Nanyingee is the spelling used on topographic maps, since 1878, although Manyingee has continued to be the local usage.

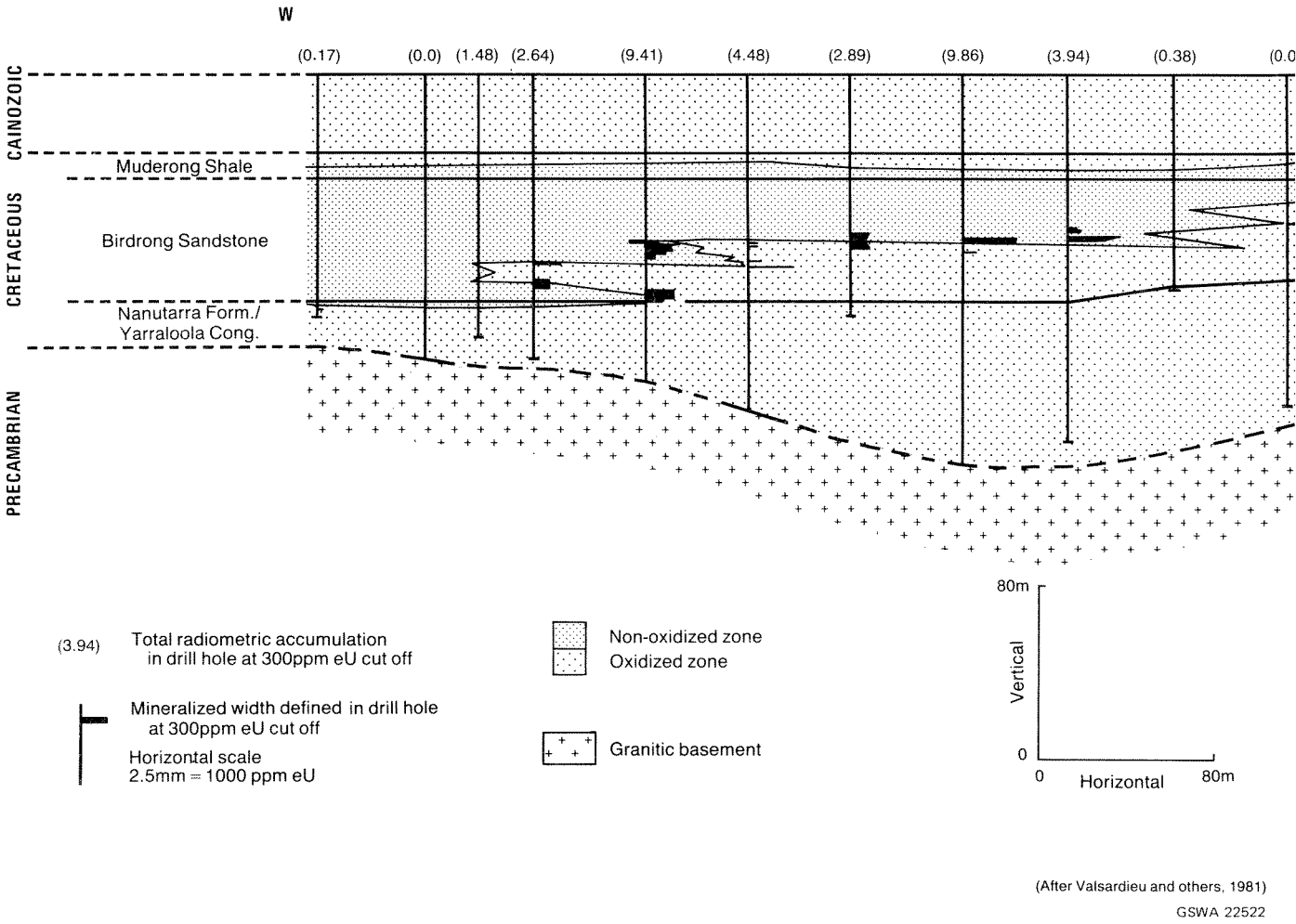

Figure 128. East-west cross-section through Manyingee 1 uranium mineralization, after Valsardieu and others (1981).

Peneconcordant deposits

There has been no exploration specifically for peneconcordant uranium mineralization in the Carnarvon Basin. However, there is considerable potential for such mineralization in a number of sequences, particularly in the Permian succession.

One exploration program by Afmeco Pty Ltd, for roll-front mineralization in the Moogooloo Sandstone, in the Pells Range area appears to have intersected mineralization akin to the peneconcordant type, and could indicate considerable potential within the Moogooloo Sandstone.

Tectono-lithologic or structural-stack deposits

Only one exploration program for this type of deposit has been reported. The program was unsuccessful possibly because the area explored was situated too far west of the basement source area. It is considered that there may be considerable potential for mineralization of this type associated with major faults along the eastern margin of the Merlinleigh Sub-basin and northern margin of the Byro Sub-basin, especially where these faults cut both the basement granitoids and Palaeozoic fluvial or deltaic sandy sequences.

Other styles of uranium mineralization

Minor occurrences of uranium minerals have been reported from limestones of the Gneudna Formation at two localities. Although both occurrences appear to be related to the recent circulation of near-surface uraniferous groundwaters, and to be of limited extent, they suggest that conditions suitable for the formation of uranium mineralization are present in the limestone, which may warrant further exploration.

Dahlkamp (1978) suggested that large-tonnage, low-grade deposits associated with black-shale and phosphorite sequences could be possible future sources of uranium. Rock units which may potentially host such deposits are present in the Carnarvon Basin, notably in the Lyons and Byro Groups in the Merlinleigh Sub-basin, and the Byro Group of the Byro Sub-basin. One minor occur-

rence of carnotite and tyuyamunite, in siltstones and claystones of the Lyons Group (Harris Sandstone), has been reported.

Although calcretes are present within many drainages on the eastern margin of the Carnarvon Basin, it seems unlikely that significant tonnages of mineralization are preserved because rejuvenation of the drainages has resulted in the better developed bodies being actively eroded into a series of terraces. The only known occurrence of uranium mineralization in calcrete is at Quail Springs, west of Lyndon Station, where minor carnotite occurs, spottily, in a veneer of calcrete developed over a highly uraniferous granite.

Harrison (1985) listed several general and specific targets, which warrant further exploration for uranium, and discussed the effectiveness of the various exploration methods which have been used within the basin.

HEAVY-MINERAL SANDS

The provenance and theoretical assemblage of potential heavy-mineral concentrations in the Carnarvon Basin were discussed by Harrison (1985). He concluded that, in the south, the heavy-mineral suite would be dominated by ilmenite, with lesser zircon and rutile. Ilmenite would be derived from basic igneous and metamorphic rocks, the zircon from granites, and the rutile from basic igneous rocks, "reworked granites and pegmatites". The Morrissey Metamorphic Belt might be expected to dilute the value of the heavy-mineral suite by providing differing quantities of 'light' heavy minerals of metamorphic origin, such as garnet, kyanite, staurolite and epidote in the central part of the basin. In the northern part of the basin the heavy-mineral suite would probably be swamped by large quantities of magnetite and titano-magnetite derived from the rocks of the Hamersley Basin and Pilbara Block.

Known results of exploration programs fit with these predictions. The most favourable potential is in the south, in the drainages of the Murchison and Wooramel Rivers, and, to a lesser extent, in the central part of the basin drained by the Gascoyne, Minilya and Wooramel Rivers. One exception to these generalizations is in the southernmost part of the coastal section of the basin, where a high proportion of garnet, derived from the Northampton Block, has been incorporated in the heavy-mineral suite. Near Gregory, the garnet is in sufficient quantity and quality to be of economic interest. This occurrence is further discussed below in the section on industrial minerals.

The sites of potential heavy-mineral accumulations along the coast are influenced by longshore drift, prevailing-wind direction, and eustatic sea-level change. In much of the basin the prevailing longshore drift is from south to north, as shown, for example by the dune sequences developed north of the Gascoyne delta, but it appears that at least locally (in the area northeast of Exmouth Gulf) there may be a southerly drift. Prevailing westerly winds have led to the formation of major systems of sand dunes and beach ridges associated with the Gascoyne, Ashburton, Robe, and Cane Rivers. Eustatic changes of sea level during the Quaternary have resulted in the formation of raised shorelines in a number of places. These shorelines and the deposits associated with them were discussed by Harrison (1985).

Tertiary sediments, although they are generally more indurated, contain a number of possible shoreline sand sequences and may also warrant consideration as targets for mineral-sand exploration.

Previous exploration

Ashburton Sands Pty Ltd and Ferrovanadium Corporation NL carried out exploration, during 1967-72, in coastal-dune sequences associated with the mouth of the Ashburton River. Two deposits, collectively known as the Onslow prospect, were outlined. These reportedly contain a total of 5.84 Mt of contained H.M., at an average grade of 10.4% H.M. using a cut-off grade of 5% H.M. Between 60% and 70% of the heavy minerals are iron oxides (mainly hematite, martite, and goethite) and the presence of a high proportion of iron-stained quartz precludes the preparation of an iron-ore product. Further details of these deposits were given by Baxter (1977).

Bamboo Creek Gold Mines NL completed reconnaissance exploration of the coastal sequences near the Robe and Fortescue Rivers. Although considerable quantities of heavy minerals were present, sampling showed that they were between 35% and 85% iron oxides with the remainder comprising mainly ilmenite and ferromagnesian minerals, with very minor zircon and garnet.

At the mouth of the Cane River on Yardie Creek Station, Vam Ltd reported reserves of 22.5 x 10^6 m^3 at 4.7% contained H.M. Once again the heavy-mineral suite was dominated by magnetite, goethite, and martite.

Concentrations of up to 80% contained H.M. have been reported on Peron Peninsula. Postholing by Coastal Titanium defined 26 700 t of

contained H.M. in ore grading 8.9% H.M. with an inferred potential for an additional 80 000 t of contained H.M. The concentrate contained 25–60% ilmenite, 4–11% leucoxene, 20% zircon, 0.5% rutile and 13% garnet with the remainder being mainly iron oxides. In 1979–80 Allied Eneabba Ltd carried out a program of vacuum drilling, concentrating on the dune deposits. Only minor concentrations were located, to a maximum of 2% H.M., forming a veneer over topographic features. It was concluded that there was no economic potential.

One program designed to search for raised shorelines was carried out by Inco in the area north of the Murchison River. A Quaternary sand plain was located in which possible coastal notches were identified. Only a low heavy-mineral content (up to 2%) was present although this had a favourable mineralogy, which included 40–42% ilmenite, 4–5% leucoxene, 10–11% rutile, 26–27% zircon, 1–1.5% monazite and 4–5% kyanite.

Potential for further exploration

Potential targets are the recent (Bejaling) and Pleistocene (Brown) beach ridges associated with the mouth of the Gascoyne River and extending for 45 km north of Carnarvon. Sampling of mineral slicks on present beaches near Carnarvon by Coastal Titanium returned a mineral concentrate containing 43% ilmenite, 13% zircon, 2% rutile and 1% monazite with the remainder being mainly iron oxides and garnet. A similar mineralogy was obtained from samples collected by the GSWA from the beach ridges, although silicate "light heavies" rather than iron oxides formed the "gangue" component. In view of the very large untested sequence and the relatively favourable infrastructure, further evaluation and drilling of this sequence is considered to be justified.

The Peron Sandstone has not been explored for mineral sands, but in the Cape Peron area north of Denham it appears to be in part the immediate source for mineralization developed on recent beaches and dunes. Sampling of the Peron Sandstone here gave assays up to 0.5% H.M. In view of the favourable mineralogy in the recent strandlines, exploration of the older eolian deposits of the Peron Sandstone appears justified. Much of this unit is unconsolidated.

The favourable mineralogy found in concentrates north of the Murchison River makes this area potentially prospective. Examination of false-colour Landsat images suggests that there may be a number of ancient courses of the Murchison River draining into this area, together with a number of features which could represent former shorelines. An area to the southwest of the Billabong roadhouse is considered to be of particular interest. Although apparent 'desert'-type dunes are present it is possible that these could be obscuring (or reworking?) former coastal sequences deposited in the vicinity of the ancient river mouths.

INDUSTRIAL MINERALS

Evaporites

The largest mining project currently in operation in the Carnarvon Basin is that owned by Dampier Salt Ltd (CRA) at Lake MacLeod. The operation was initially proposed to produce langbeinite – $K_2Mg_2(SO_4)_3$ – from potash-rich lake brines, and a potassium sulphate plant, with an annual production of 200 000 t, was installed. Production from this plant has been restricted, due to economic factors, and the main product has been solar salt.

The Lake MacLeod basin includes an evaporite sequence at least 12 m thick, containing salt, gypsum, and sylvite. Salt production is from evaporative pans on the western side of the lake. These are filled by pumping from ditches which tap seepages of near-saturated brines from a thick halite bed. Annual production, normally between 1.1 and 1.6 Mt, is shipped from a jetty at Cape Cuvier. Production for 1984 was 623 000 t.

Shark Bay Salt Pty Ltd operates a solar-salt plant at Useless Loop, on the Freycinet Estuary at Shark Bay. Sea water is concentrated in a system of evaporation and crystallizer ponds which are lined by plastic sheeting. Production for 1984 was 627 951 t.

Evaporites are present in the Yaringa Evaporite Member of the Dirk Hartog Formation, and in the Sweeney Mia Formation. Anhydrite was first found in Dirk Hartog 17B in 1957, while halite was discovered in Yaringa 1. This discovery prompted the drilling of two holes, Hamelin Pool 1 and 2, specifically to test the potential of the evaporites.

Yaringa 1 intersected 36.2 m of halite in eight beds; Hamelin Pool 1 drilled 22.9 m of salt in seven beds; while Hamelin Pool 2 intersected 5.2 m of salt in 3 beds (Wells, 1980). Sylvite is present in small amounts in the salt beds of Yaringa 1 suggesting some potential for economic potash mineralization. The marked thinning in Hamelin Pool 2 has been taken as indicating that this is near the margin of the basin (Wells, 1980).

But at the depth at which the beds were intersected (greater than 1000 m) variations in thickness could result from plastic flowage of the halite.

Simple geometry suggests that the Yaringa Evaporite Member should occur closer to the surface in the area north of Kalbarri 1 well and thus be a potential target for potash exploration. In this general area there are zones of greatly increased salinity, in both the confined (Birdrong Sandstone) and unconfined groundwater (see section on Groundwater). These could derive from evaporites in the (Silurian) basement rocks.

A second evaporite-carbonate suite, the Sweeney Mia Formation, is present in the upper parts of the Yaringa and Hamelin Pool wells. Although no halite was intersected, extensive beds of anhydrite or gypsum interbedded with dolomite are present, from 174 m to 230 m in Yaringa 1, 241 m to 262 m in Hamelin Pool 1, and 235 m and 268 m in Hamelin Pool 2. These suggest that evaporite minerals of potential economic interest could occur elsewhere within the basin. The Sweeney Mia Formation probably forms subcrops at a shallow depth beneath a thin cover of Cainozoic and Cretaceous sediments in the area south of Shark Bay (Fig. 14).

Gypsum is another evaporite mineral of considerable economic significance within the Carnarvon Basin. A major mining project is operated by Agnew Clough Ltd, 6 km south of Useless Loop. In this area a number of isolated bedded deposits of gypsum have formed as a result of the evaporation of sea water in minor barred basins at the heads of ancient inlets. All production from the Shark Bay project is exported, mainly to Japan and southeast Asia. Production has risen from 74 609 t in 1974, to 348 144 t in 1984.

Widespread, thick deposits of gypsum are present in the Lake MacLeod basin, where drilling during the initial investigation of the evaporite deposits revealed thick beds of gypsum below the lake surface. Difficulty of extraction makes these reserves uneconomic at present. Extensive reserves are also present in a flat basin extending for some 15 km north of Lake MacLeod, in the vicinity of the mouth of the Lyndon River.

In 1971, Great Boulder Gold Mines Ltd announced that deposits estimated to contain 100 Mt of gypsum, at a grade in excess of 90% $CaSO_4.2H_2O$, had been located in the basin north of Lake MacLeod.

Further deposits of gypsum both in bedded and 'seed' (or "kopai") form are present to the east of Lake MacLeod just north of the boundary between Boolathana and Boologooro stations (Connolly, 1960). Reserves were conservatively estimated at approximately 9.5 Mt of bedded gypsum of variable grade (approximately 82% to > 97% $CaSO_4.2H_2O$).

Bentonite

Bentonitic sequences are present in the Muderong Shale and Gearle Siltstone. The Gearle Siltstone in the Giralia Anticline was investigated by Garrick Agnew Pty Ltd in 1963–66. The clay consists of saponite mixed with kaolinite and illite. Oxide components of the bentonite are:

Oxide	*%*
SiO_2	53.5
Al_2O_3	17.7
Fe_2O_3	8.38
MgO	2.22
CaO	0.18
Na_2O	1.53
K_2O	1.29
TiO_2	0.67

Potential reserves were estimated to be about 300 Mt.

Barite

Barite, in the form of large septarian nodules, is present over much of the outcrop area of the Gearle Siltstone in the Giralia Anticline. These are the surface expression of stratiform, bedded deposits, up to 40 cm thick, apparently deposited in a series of local basins. Although the deposits are mostly friable and low grade, a very extensive tonnage is present.

Veins carrying barite, with minor galena and sphalerite, occur in both basement gneiss and overlying Harris Sandstone approximately 10 km south of Mount Sandiman homestead (Fig. 129). Some of the veins have been opened up by shallow prospect pits, while others have not been systematically sampled.

Garnet

Garnet sands near Port Gregory are being mined by Target Minerals NL from one of the few mines in the world where garnet is the main commercial product.

The deposit is situated on a Late Pleistocene shoreline on the east side of Hutt Lagoon. It contains indicated reserves of 6.1 Mt contained H.M. at an average grade of 22.8% H.M. Garnet rep-

GSWA 22523

Figure 129. Stereo pair of barite vein within basal Harris Sandstone, Mount Sandiman. Vein has been excavated, and Harris Sandstone forms walls of trench.

resents 83% of the H.M. content. Within the mine-development area a zone containing prime 'clean' coarse sand averaging 42% H.M. has been delineated. The sand is mined by scrapers, dozers, and front-end loaders. It is beneficiated by wet gravity-separation on site, and is further processed at Geraldton.

Phosphate

A number of companies have carried out broad regional surveys for phosphate within the Carnarvon Basin, concentrating on the Cretaceous and Permian successions. Although drilling programs were undertaken, no significant deposits were discovered.

Thin and discontinuous bands of phosphate (as nodules and phosphatized wood) occur in the Alinga Formation and Toolonga Calcilutite. Thin phosphatic beds are also present in the Miria Formation and Boongerooda Greensand Member. These occurrences are apparently of no economic significance. A number of siltstone sequences in the Byro Group contain phosphate networks, and assays up to 1.25% P_2O_5 have been reported. There could be some potential for the development of economic deposits especially within the Bulgadoo and Quinnanie Shales.

Fullers Earth

Deposits of attapulgite clay, a variety of fullers earth, of good quality, are mined from time to time by Mallina Holdings Ltd from the Lake Nerramyne area near the southern margin of the basin.

Limestone

Vast quantities of limestone are present in the Palaeozoic and Cainozoic sequences. Minor local use has been made of the Palaeozoic limestones, especially the Moogooree Limestone and Callytharra Formation, as building stones, while several of the younger sequences have been used in road building.

Cainozoic limestones, especially the Trealla Limestone, have been investigated for their use as fluxes in the steel industry. The limestone of the

Cape Range area was investigated by The Broken Hill Proprietary Co. Ltd (BHP) in 1961, 1962, and 1964 (McEwen, 1964). Testing was also carried out in 1973–1974. A typical better quality limestone from the Cape Range area contains 0.83% SiO_2, 54.665% CaO, and 0.23% MgO, whereas a typical sample of poorer quality dolomitic limestone from this area contains 0.75% SiO_2, 34.4% CaO, and 17.2% MgO. Phosphorus content is commonly below 0.02% and no sample tested was above 0.074%. Inferred resources, in a 1.6 km square block with a mean depth of 30 m above base-creek level, were estimated by B.H.P. to be 80–90 Mt of limestone. Part of the limestone resources are now within the Cape Range National Park.

Limestones on QUOBBA were found to have deleterious amounts of silica, precluding their use as a flux. Limited testing of these deposits was also completed by the Hancock and Wright group.

GROUNDWATER

(A. D. Allen)

INTRODUCTION

Historical

When the Carnarvon Basin was first settled during the 1860s, pastoral supplies were obtained from a few riverine pools and shallow wells. In the 1890s, after the discovery of the Great Artesian Basin and its large-scale exploitation, interest was directed at obtaining artesian groundwater in the Carnarvon Basin. In 1903 the Western Australian Government drilled an exploratory bore for water and coal near Carnarvon (Bibbawarra or Pelican Hill bore) and encountered a large flow of warm brackish groundwater. This demonstrated the artesian-groundwater potential for part of the basin.

During the following 30 years about 100 artesian bores were drilled and artesian or sub-artesian water was proven over about one-third of the basin. In the remainder, either it was not available, or shallow unconfined groundwater was utilized.

During the 1930s, banana growing and (later) market gardening started at Carnarvon, using water supplies obtained from the river-bed sand of the Gascoyne River and from adjacent alluvium. The fresh groundwater supplies are small and rely on periodic flows of the Gascoyne River for replenishment. Strict licensing of groundwater abstraction was introduced by the Government in the 1960s, and since the early 1970s the Government has undertaken the supply of a large proportion of the water used for irrigation.

Since 1960 there has been a general upgrading and extension or development of new water supplies for the major towns. In addition there has been some development of water supplies for mining operations, defence facilities at Exmouth, road construction, gas-pipeline construction, and tourist facilities. During the same period there has been very limited development for the pastoral industry.

Data

Systematic assessment of the groundwater resources in the Carnarvon Basin has only been done along the lower reaches of the Gascoyne River and on the floodplains of the Fortescue and Robe Rivers. Some detailed data are available for many artesian bores and for bores drilled for various town-water supplies. Elsewhere (excluding Carnarvon), general data obtained during regional geological mapping are available for about 1400 pastoral bores. Groundwater analyses for some of these bores are given in Table 7.

Brief, regional descriptions of the groundwater resources for all, or large parts of the basin, were given by Maitland (1913), Mackay (1963), Condon (1965b, 1967, 1968), Balleau (1973), Davidson (1975), Bestow (1976), and in various explanatory notes. Quantitative estimates have been given in reviews of Australia's water resources (Anon, 1965, 1976).

Descriptions of local groundwater resources along the lower reaches of the Gascoyne River were given by Baxter (1967), Passmore (1968), and Allen (1972b, c). Local fresh groundwater resources on the floodplains of the Robe and Fortescue Rivers are currently (1986) being investigated.

The Carnarvon town and irrigation water supplies were described by Allen (1972b), and Exmouth water supply by Forth (1973). The Public Works Department (PWD) published reviews of the operations of the town-water supplies of Onslow (Ventriss and Parsons, 1979), Exmouth (Ventriss and Parsons, 1978a), Carnarvon (Ventriss, 1980), Gascoyne Junction (Ventriss and Smith, 1979), and Kalbarri (Ventriss and Parsons, 1978b; Anon, 1983).

There are also unpublished oil, mining, and consultants' reports concerning aspects of the hydrogeology. The most important of these are reports by WAPET on hydrogeological aspects of

the Birdrong Sandstone (McWhae, 1958) and a listing of water-bore logs by Playford and Chase (1955).

Drainage

Ten large rivers traverse the Carnarvon Basin (Figs 5, 6), and of these the Gascoyne, Murchison, Ashburton and Fortescue Rivers are among the largest rivers in Western Australia. The catchments of the major rivers extend inland beyond the basin margin, for about 500 km, to a continental divide separating seaward-draining rivers from a sluggish internal-drainage system. In the eastern part of the basin the rivers tend to be incised and well defined, whereas on the coastal plain they have braided and anastomosing courses, associated with prograding floodplains. An exception to this general pattern is the Murchison River, the lower part of which flows through a deep gorge.

The total catchment of the rivers flowing across the basin is about 410 000 km^2. However, despite the size of the river catchments the variability of rainfall results in intermittent flows with occasional major floods. The flows are generally fresh with the exception of the brackish Murchison River.

OCCURRENCE OF GROUNDWATER

General

For convenience the groundwater resources are described in two parts: unconfined groundwater, which occurs in a multi-formational aquifer system; and confined groundwater, in two major confined aquifers. Notes on the groundwater potential of the main formations recognized in the basin are given in Table 6, and Figure 130 shows diagrammatically the commonest sites of successful bores.

Unconfined water occurs in near-surface sediments, and a water table extends throughout the basin. The unconfined groundwater is locally in hydraulic connection with underlying stratigraphically and/or structurally confined, artesian and subartesian aquifers.

The major aquifers consist of porous and permeable sandstone, limestone, sand, and gravel, generally in extensive, structurally uncomplicated units of Silurian, Cretaceous, and Cainozoic age.

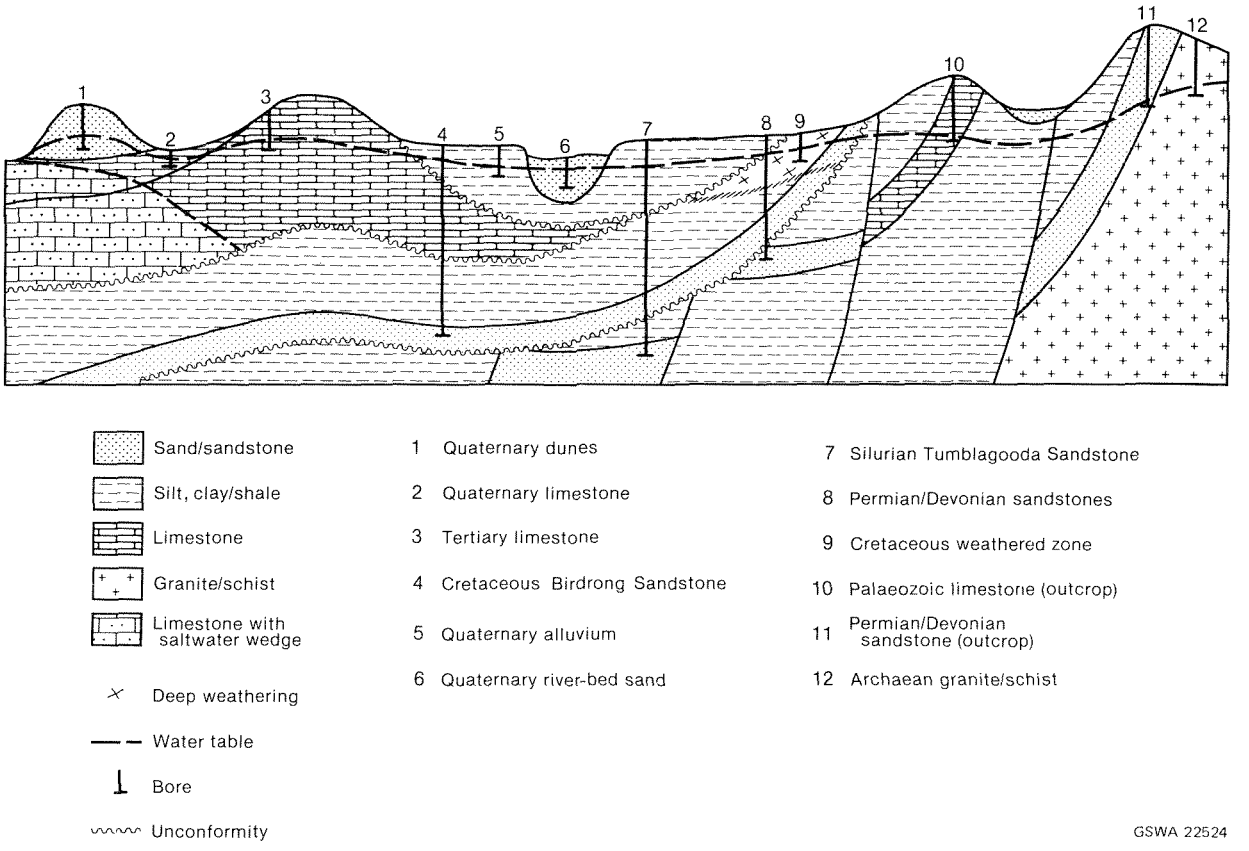

Figure 130. Common successful bore sites in the Carnarvon Basin.

Unconfined groundwater

The unconfined groundwater occurs in a major flow system within contiguous near-surface sediments. Minor, local, flow systems occur beneath offshore islands, and as perched flow systems, mainly in the Kennedy Range. The groundwater occurs at or near the surface along the beds of the major rivers, and to depths of about 100 m in some elevated areas. On the coastal plain the water table (Fig. 131) is relatively uniform, sloping gently towards the sea, but in the dissected eastern part of the basin it is complex and cannot be mapped on a regional scale.

In the eastern part of the basin, recharge to the unconfined groundwater occurs from direct infiltration of rainfall in areas of prominent outcrop, and from runoff in streams above the base level of the major drainage lines. On the coastal plain, direct rainfall recharge occurs on areas of limestone and sand, and from river flows, as indicated by the prominent ridge in the water table along the Gascoyne River (Fig. 131). Elsewhere on the coastal plain, direct recharge possibly does not occur or is only an occasional event because of the clayey nature of much of the alluvium.

Groundwater flow in the eastern part of the basin is largely controlled by the topography. Most groundwater flow appears to be directed towards the major rivers. On the coastal plain, groundwater flow is away from the rivers and westwards to the sea.

Local groundwater discharge from unconfined groundwater in the upland area occurs via riverine pools and springs. On the coastal plain, springs are virtually absent except in some areas of limestone, and groundwater probably discharges into the sea over a salt-water wedge along the length of the coast. Other significant discharge on the coastal plain is by evapo-transpiration from vegetation along rivers, particularly upstream of Rocky Pool on the Gascoyne River, and along the lower reaches of the Fortescue River.

The salinity of the unconfined groundwater ranges from about 200–12 000 mg/L TDS (Fig. 132). Fresh groundwater (less than 1000 mg/L TDS) is obtainable over about 5% of the basin in the vicinity of intake areas. The groundwater salinity tends to show a systematic increase in the direction of groundwater flow. Exceptions are: saline groundwater in the southern part of the basin, which may be due to solution of evaporites in Silurian sediments; and very saline groundwater on the coastal plain to the east of Exmouth Gulf, which may be partly relic seawater. Locally, high concentrations of boron and fluoride affect the quality of the groundwater.

Bores or wells into the unconfined groundwater generally range from 5 to 60 m deep and average about 30 m. Most pastoral supplies are equipped with windmills and yield about 5 m^3/d. Town water-supply bores in river-bed sand may yield up to 3000 m^3/d; in Silurian sandstone 500–1000 m^3/d; and in alluvium 1500–2000 m^3/d.

Confined groundwater

Confined groundwater in the Carnarvon Basin occurs mainly in the Birdrong Sandstone and Tumblagooda Sandstone. It also occurs in some thin sands interbedded in Cretaceous shales and in Palaeozoic sandstones, but usually in small quantities and of unacceptable salinity. The rock units containing confined groundwater resources are overlain and underlain, to varying degrees, by less permeable confining beds. They extend over large areas and into the offshore part of the basin.

The Birdrong Sandstone is about 20–30 m thick and extends over about 77 000 km^2 of the onshore part of the basin (Fig. 133). The Muderong Shale or Windalia Radiolarite overlie and confine groundwater in the sandstone. Recharge of the Birdrong Sandstone is limited to relatively small areas where the formation outcrops (Fig. 134), subcrops, or fills palaeochannels along the eastern edge of the coastal plain. Recharge presumably occurs from: direct rainfall on outcrops; river flow where the major rivers cross areas of outcrop; and from the unconfined groundwater, where the formation subcrops immediately below younger sediments. Upward recharge from the underlying Palaeozoic sediments may also take place at unconformities where there are sandstone on sandstone contacts, or via faults.

Isopotential formlines (Fig. 134), based on non-synoptic data for bores mainly drilled between 1905 and 1930, show the approximate configuration of the potentiometric surface. The present configuration may be significantly different, as large uncontrolled flows have occurred from many bores for about 70 years. The direction of groundwater flow is generally westward, except for some apparent northward flow in the southern part of the basin. Estimates of groundwater velocities indicate flow rates of about 4 m/y.

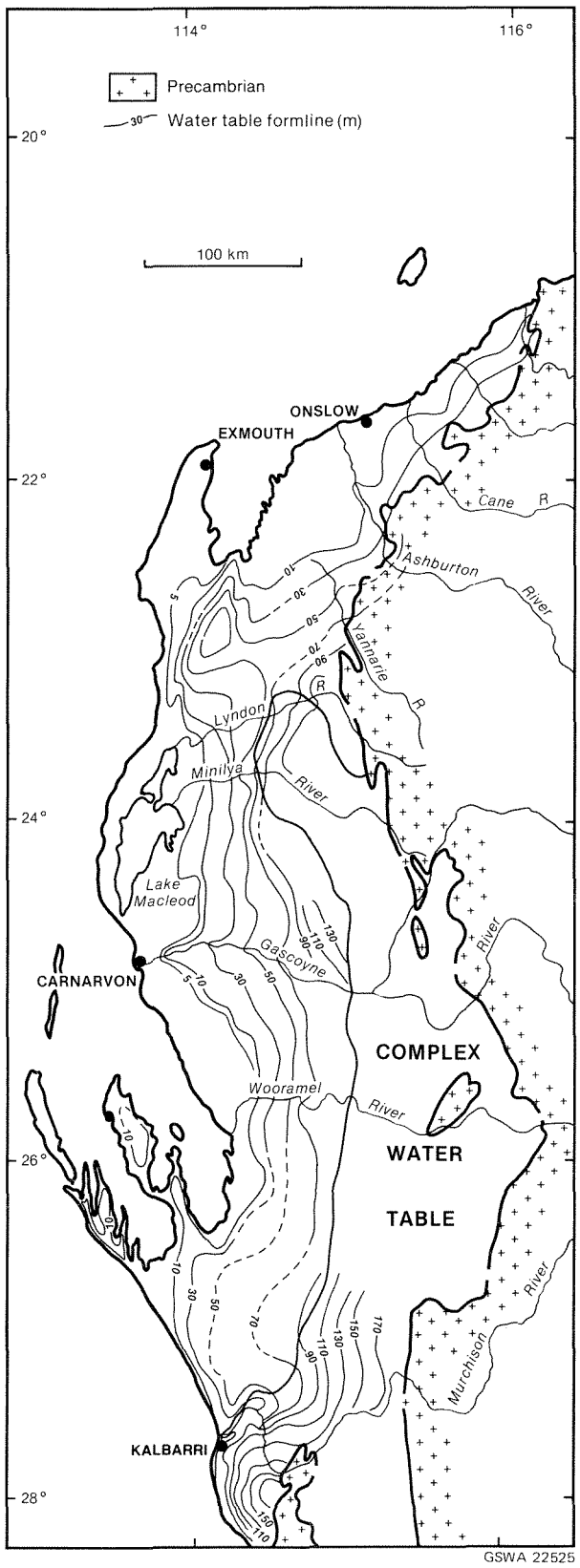

Figure 131. Water-table elevation in the Carnarvon Basin.

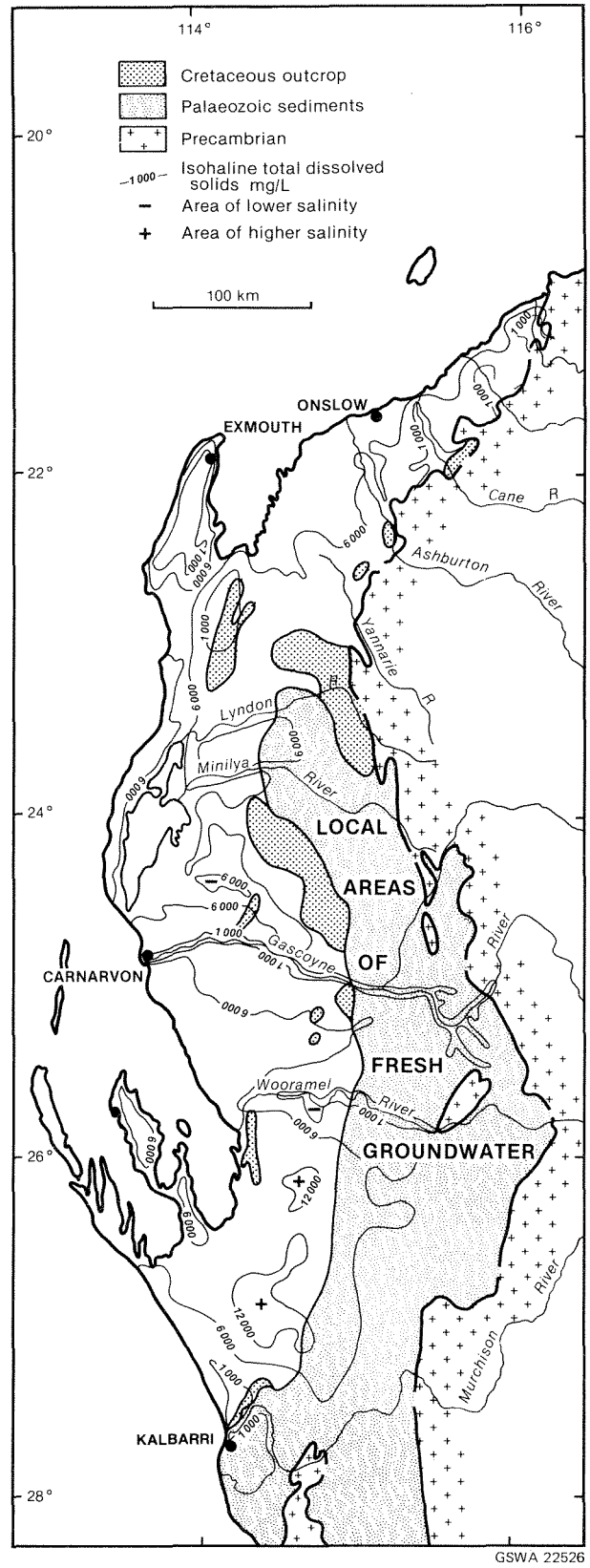

Figure 132. Salinity of unconfined groundwater.

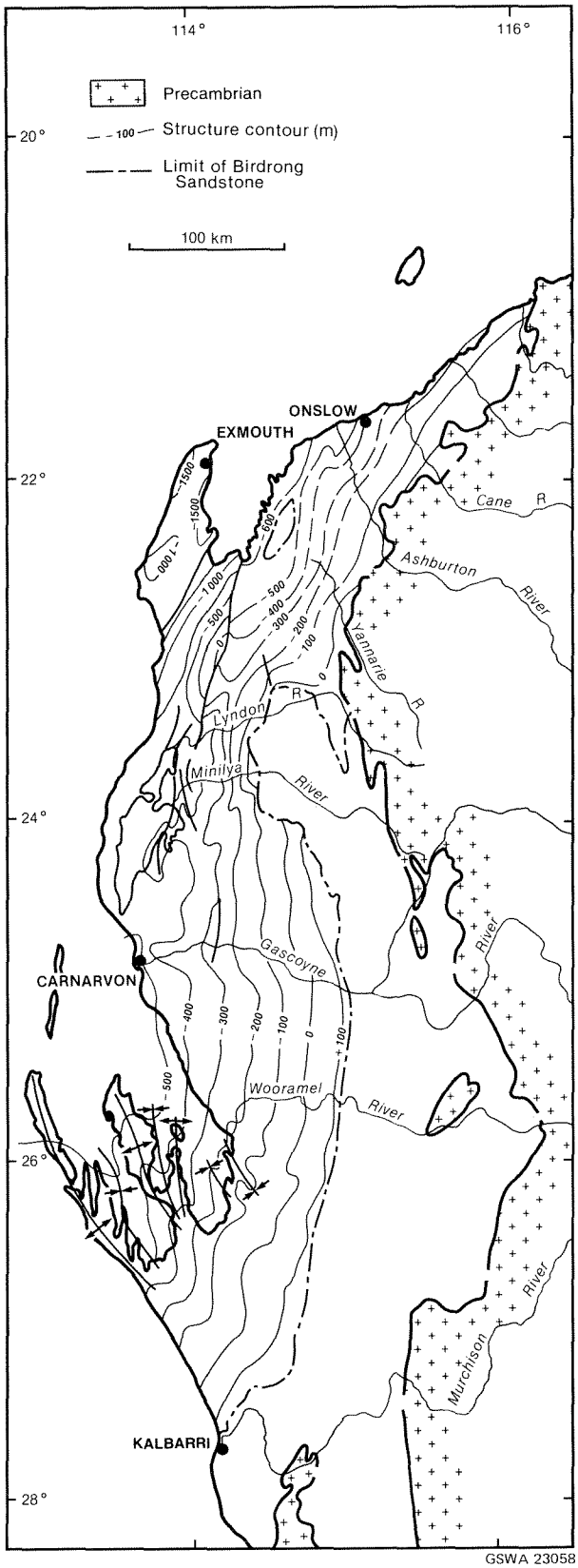

Figure 133. Depth to Birdrong Sandstone, relative to sea level.

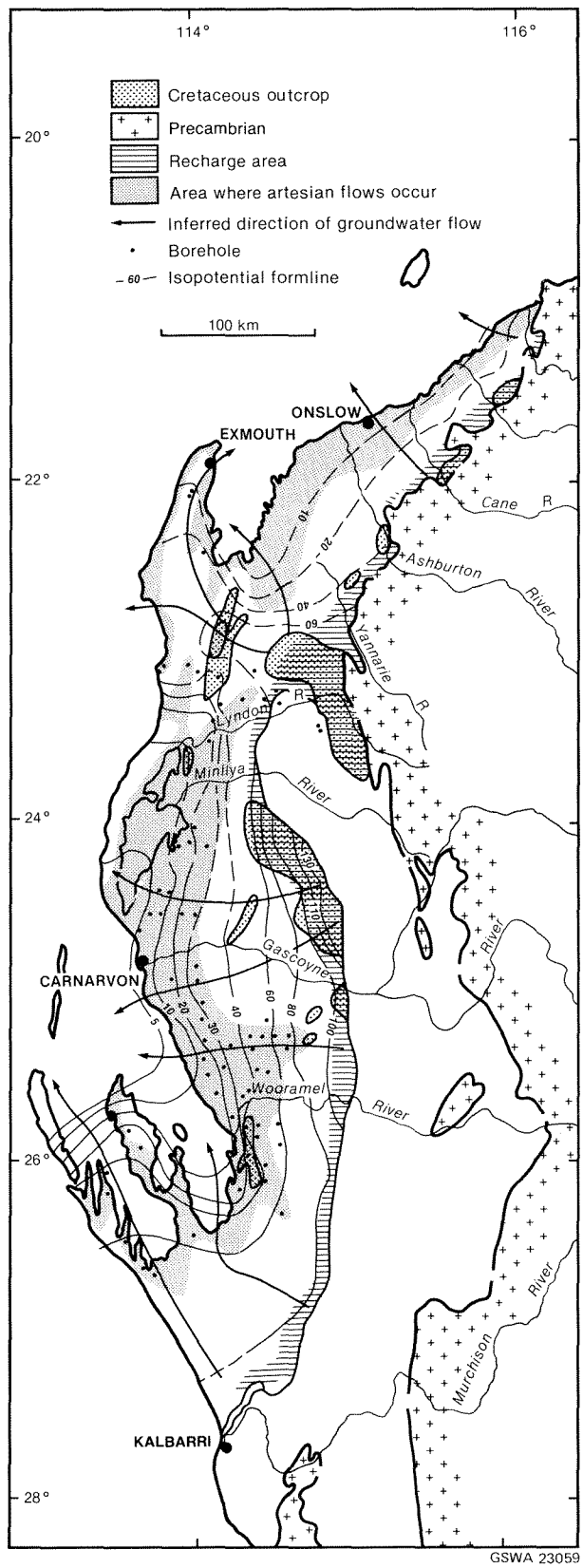

Figure 134. Isopotential formlines of groundwater in the Birdrong Sandstone.

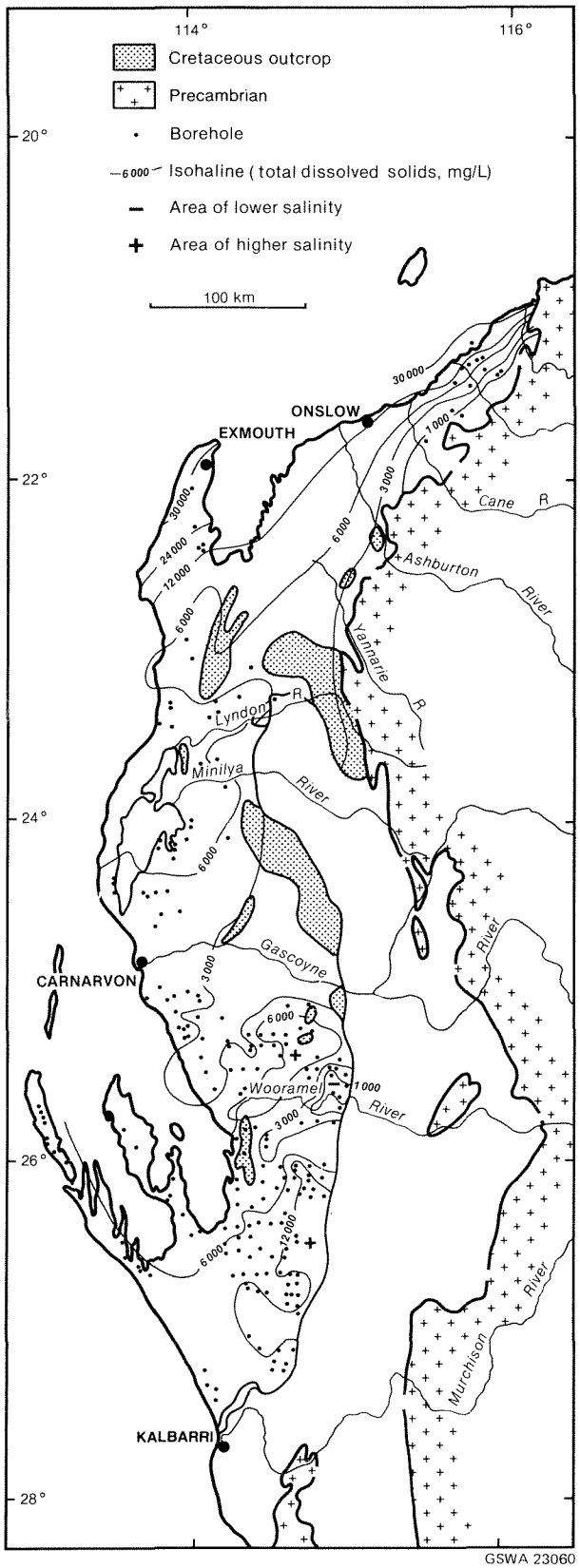

Figure 135. Groundwater salinity in the Birdrong Sandstone.

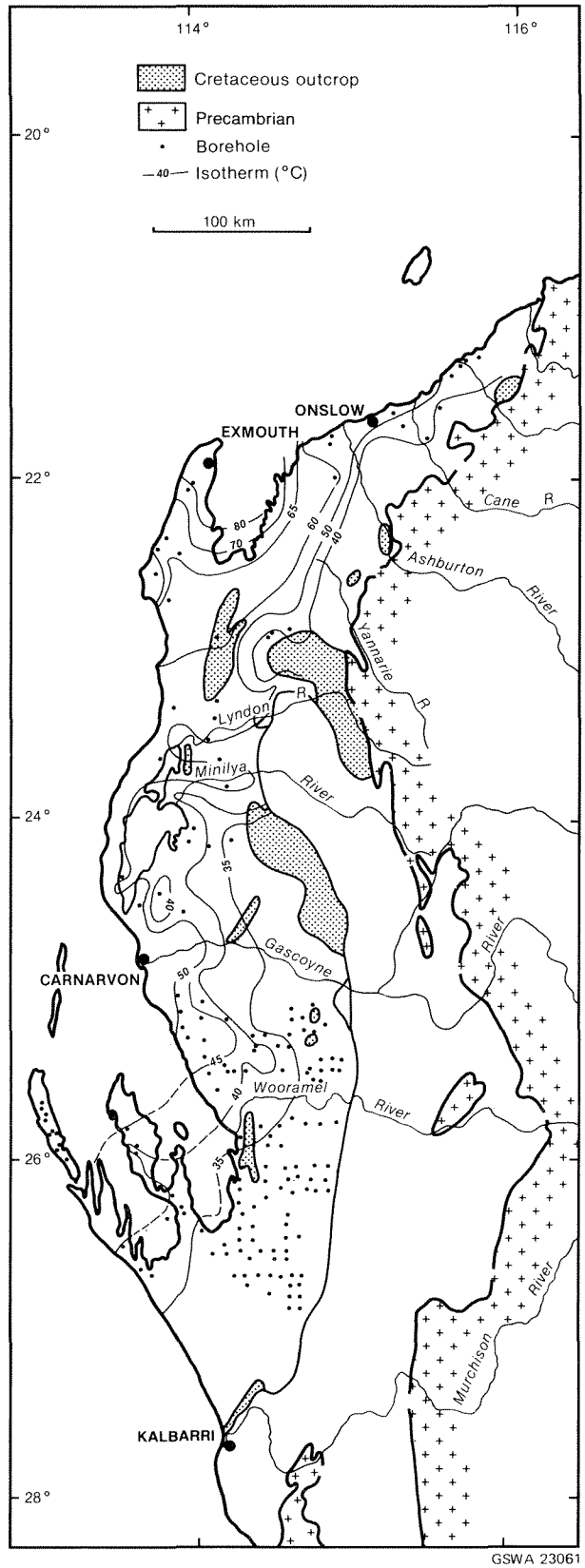

Figure 136. Groundwater temperature in the Birdrong Sandstone.

Discharge from the Birdrong Sandstone may be occurring by upward leakage through confining beds or by piping along faults into overlying Cainozoic sediments near the coast. The isopotentials suggest groundwater discharge in the vicinity of Exmouth Gulf, Lake MacLeod and Shark Bay. Actual discharge (presumed to be from the Birdrong Sandstone) occurs on the coastal plain between the Robe and Fortescue Rivers at Mount Salt (Williams, 1965). This is a large, active, mound spring with an anomalously high head. Other inferred discharge is occurring via collapsed and leaking artesian bores in the artesian areas shown in Figure 134.

The salinity of groundwater in the Birdrong Sandstone varies from about 500 to 34 000 mg/L TDS and averages about 6000 mg/L TDS (Fig. 135). Fresh groundwater is restricted to intake areas where the Fortescue, Robe, Lyndon, Gascoyne and Wooramel Rivers cross the outcrop or subcrop of the formation. In other areas of outcrop the groundwater is brackish, possibly reflecting low-recharge rates and evapotranspiration from where groundwater is unconfined in the sandstone. There is a general increase in salinity in the direction of groundwater flow. An area of high salinity in the southern part of the basin may be attributable to the solution of evaporites in underlying Silurian sediments. Steep salinity gradients in the vicinity of Cape Range and the Onslow coast may result from up-dip migration of saline groundwater, expelled by compaction of sediments in the offshore part of the basin (Thomas, 1978). The general groundwater salinity suggests that the sandstone has been water-flushed, so that in most areas there are only slight possibilities of hydrocarbons.

Iron, manganese, silica, hydrogen sulphide, and carbon dioxide are troublesome in groundwater from some bores. Natural gas has been reported from Coburn No. 4 bore, and droplets of oil occur in water flowing from the Mauds Landing bore. Groundwater temperatures vary from about 32°C to 80°C (around Cape Range and Onslow), and increase in the direction of groundwater flow (Fig. 136). Moors (1980) noted geothermal anomalies along the Onlsow coast, and Bestow (1982) discussed the geothermal-energy potential of this area, and other parts of the basin.

Bores range in depth from 100 to 900 m and average 200 m. Flows range from about 500 to 4500 m^3/d and average about 1250 m^3/d. The flow from most artesian bores is uncontrolled and the total estimated discharge is about 50 x 10^6 m^3/y.

The Tumblagooda Sandstone contains fresh to brackish unconfined groundwater (Fig. 132) with the water table 150 to 200 m above sea level in the area of outcrop along the Murchison River. Further north the groundwater in the formation is confined beneath Cretaceous or Palaeozoic sediments.

The configuration of the potentiometric surface is not known but groundwater flow is presumed to be northwards from the recharge area near Kalbarri. In Bibbawarra bore the head in the Tumblagooda Sandstone was about 50 m higher than in the overlying Birdrong Sandstone and the salinity about 1000 mg/L TDS less, indicating an active, relatively well-flushed, flow system. Discharge from the formation presumably occurs along fault lines into the overlying Birdrong Sandstone and Tertiary limestones.

The salinity of groundwater in the area of outcrop is generally less than 1000 mg/L TDS, and groundwater of this salinity is known to extend to at least 150 m below sea level at Kalbarri. The salinity is inferred to increase northwards and is 4600 mg/L TDS in the Bibbawarra bore. Minor evaporites in the overlying Dirk Hartog Formation may contribute to the salinity. The groundwater had a temperature of about 60°C in the Bibbawarra bore and the formation may be a future source of geothermal energy (Bestow, 1982).

The artesian flow recorded from the Bibbawarra bore was 2340 m^3/d; and bores abstracting unconfined groundwater in the outcrop area at Kalbarri yield 500–1000 m^3/d.

UTILIZATION OF GROUNDWATER RESOURCES

Despite the number of large rivers which cross the basin, the geology and climate have combined to limit the availability of fresh water. Groundwater is virtually the only permanent source of water in the Carnarvon Basin, and potable supplies are limited to about 5% of the basin. In the rest of the basin, brackish to saline unconfined groundwater and brackish artesian groundwater may be available. However, in areas underlain by some Palaeozoic siltstones and shales, usable groundwater resources are locally unobtainable because of salinity and low yields. Usage is shown in Table 8.

Fresh unconfined groundwater is utilized for the Onslow, Exmouth, Carnarvon, Gascoyne Junction, and Kalbarri town-water supplies. It is also

utilized for large-scale irrigation of banana plantations and market gardens at Carnarvon, and (where available) for domestic and some stock supplies on pastoral properties. Brackish to saline unconfined groundwater is used extensively for stock-water supplies throughout the basin.

Brackish, artesian and sub-artesian groundwater is used extensively in parts of the coastal plain where the unconfined groundwater is salty, or only available in small supplies. The artesian flows are mainly from the Birdrong Sandstone and, with few exceptions, they are uncontrolled; a large volume of groundwater flows to waste.

Desalinization (reverse osmosis) of brackish groundwater from the Birdrong Sandstone, is carried out for the Denham town-water supply, and for solar-salt mining companies at Lake MacLeod (Texada Mines) and Useless Loop (Agnew-Clough Pty Ltd). It is probably the only method for obtaining moderate supplies of fresh water in most areas of the basin.

TABLES

TABLE 1. PERSONNEL INVOLVED IN CARNARVON BASIN 1:250 000 MAPPING AND EXPLANATORY NOTES.

Year	*Map Sheet*	*Personnel*	*References*
1975	Yanrey-Ningaloo	W. J. E. van de Graaff, P. D. Denman, R. M. Hocking	van de Graaff and others (1980)
	Onslow	W. J. E. van de Graaff, P. D. Denman, R. M. Hocking	van de Graaff and others (1982)
1976	Quobba	P. D. Denman, W. J. E. van de Graaff	Denman and van de Graaff (1982)
	Mount Phillips	W. J. E. van de Graaff, R. M. Hocking	Williams, Williams, Chin, and others (1983)
	Glenburgh	W. J. E. van de Graaff, R. M. Hocking, P. D. Denman	Williams, Williams, and Hocking (1983)
	Byro	W. J. E. van de Graaff, R. M. Hocking	Williams, I. R., and others (1983)
	Kennedy Range (part)	W. J. E. van de Graaff, R. M. Hocking, P. D. Denman	(see below, 1979)
1977	Wooramel (part)	W. J. E. van de Graaff, P. D. Denman, R. M. Hocking, B. P. Butcher	(see below, 1979)
	Yaringa	W. J. E. van de Graaff, P. D. Denman, R. M. Hocking, B. P. Butcher	van de Graaff and others (1983)
	Shark Bay-Edel	W. J. E. van de Graaff, R. M. Hocking, B. P. Butcher	Butcher and others (1984)
	Ajana	W. J. E. van de Graaff, R. M. Hocking, B. P. Butcher	Hocking, van de Graaff, and others (1983)
1978	Winning Pool-Minilya	R. M. Hocking, I. H. Lavaring	Hocking, Williams, Lavaring, and Moore (1985)
1979	Kennedy Range	R. M. Hocking, P. D. Denman, P. S. Moore, I. H. Lavaring	Hocking, Williams, Moore, and others (1985)
	Wooramel	R. M. Hocking, P. D. Denman, P. S. Moore	Denman and others (1985)

Mapping earlier than 1975: Dampier-Barrow Island (Kriewaldt, 1964), Yarraloola (Williams, 1968)

TABLE 2. TYPE SECTION DATA

Name of unit	*Derivation of name*	*Type locality*	*Type section coordinates* *Latitude (S)* D M S	*Longitude (E)* D M S	*Thickness (m)*	*Comments*
		SILURIAN				
KALBARRI GROUP	Kalbarri town (AJANA)					Contains entire Silurian sequence
Tumblagooda Sandstone	Tumblagooda Hill (AJANA)	Murchison River, Hardabut Fault to Second Gully	27 52 40 to 27 37 20	114 33 30 114 12 10	>1000	No exposed base or top, consists of numerous partial sections, faults inhibit correlation
Dirk Hartog Formation	Dirk Hartog Island (SHARK BAY)	Dirk Hartog 17B, 665–1404 m	25 51 02	113 04 47	739	Does not outcrop
Yaringa Evaporite Member	Yaringa Station (WOORAMEL)	Yaringa 1, 1195–1271 m	26 03 58	114 21 35	76	Does not outcrop
Kopke Sandstone	Kopke Point (WOORAMEL)	Yaringa 1, 326–855 m	26 03 58	114 21 35	529	Does not outcrop
Sweeney Mia Formation	Point Sweeney Mia (YARINGA)	Yaringa 1, 146–326 m	26 03 58	114 21 35	180	Eroded top
		DEVONIAN				
Nannyarra Sandstone	Nannyarra paddock, Moogooree Station (KENNEDY RANGE)	6 km south of Gneudna Well, Williambury	23 58 10	115 12 40	59	Location detailed by Condon (1965b, Fig. 10)
Gneudna Formation	Gneudna paddock, Williambury Station (WINNING POOL)	6 km south of Gneudna Well	23 58 10 to 23 58 20	115 12 40 115 12 20	?517	Remeasurement of type section gave 435–440 m. Location see Condon (1965b, Fig. 10)
Point Maud Member	Point Maud (MINILYA)	Pendock 1, 1289–1609 m	23 17 02	113 20 10	320	Does not outcrop
Munabia Sandstone	Munabia paddock, Williambury Station (WINNING POOL)	1 km north of Gneudna Well	23 54 50 to 23 54 30	115 11 50 115 11 20	555	Consists of 2 partial sections. Location see Condon (1965b, Fig. 18)
Willaraddie Formation	Willaraddie Creek, Williambury Station (WINNING POOL)	7 km southeast of Williambury homestead	23 54 30 to 23 54 40	115 11 20 115 10 40	294	Consists of 2 partial sections. Location see Condon (1965b, Fig. 18)

TABLE 2. TYPE SECTION DATA (continued)

Name of unit	*Derivation of name*	*Type locality*	*Type section coordinates* *Latitude (S)* D M S	*Type section coordinates* *Longitude (E)* D M S	*Thickness (m)*	*Comments*
		EARLY CARBONIFEROUS				
Moogooree Limestone	Moogooree Station (KENNEDY RANGE)	6 km southeast of Williambury homestead	23 54 40 to 23 53 53	115 10 40 115 10 50	326	Consists of 3 partial sections. Location see Condon (1965b, Fig. 18)
Williambury Formation	Williambury Station (WINNING POOL)	4 km southeast of Williambury homestead	23 52 40 to 23 52 40	115 10 20 115 09 50	235	Poorly exposed. Location see Condon (1965b, Fig. 27)
Yindagindy Formation	Yindagindy Creek, Williambury Station (WINNING POOL)	4 km west of Williambury homestead	23 51 40	115 06 20	76	Poorly exposed, some better exposures near Moogooree homestead
Quail Formation	Quail 1 (WINNING POOL)	Quail 1, 2100–2452 m	23 57 09	114 30 04	352	Does not outcrop. May correlate with outcrop sequence
		LATE CARBONIFEROUS AND EARLY PERMIAN				
LYONS GROUP	Lyons River (KENNEDY RANGE, MOUNT PHILLIPS)	North side of Wyndham River	25 02 20 to 25 02 50	115 42 10 115 03 30	Unknown	Poorly exposed, does not cover base or top of group, faulted, dips uncertain
Harris Sandstone	Harris Well (WINNING POOL)	8 km northwest of Williambury homestead	23 48 20	115 05 50	85	
Carrandibby Formation	Carrandibby Range (GLENBURGH)	1 km west of Callytharra Spring, south bank of Wooramel River	25 53 00	114 59 40	59	Location see Condon (1967, Fig. 60)
		EARLY PERMIAN				
UNGROUPED UNIT						
Callytharra Formation	Callytharra Spring (GLENBURGH)	0.5 km west of Callytharra Spring, south bank of Wooramel River	25 53 30	115 30 00	101	Upper hard calcarenite facies not present. Location see Condon (1967, Fig. 60)
WOORAMEL GROUP	Wooramel River (WOORAMEL, GLENBURGH)					
Cordalia Sandstone	Cordalia Well, Mia Mia Station (WINNING POOL)	Immediately east of Round Hill, Winning Station	23 20 50	114 39 30	61	Location see Condon (1967, Fig. 68)
Moogooloo Sandstone	Moogooloo Hill (WINNING POOL)	Immediately east of NMF 575, south end of Gooch Range	23 51 10	114 48 30	57	Location see Condon (1967, Fig. 72)

Billidee Formation	Billidee Well, Moogooree Station (KENNEDY RANGE)	1 km west of Toby Bore, Moogooree Station	24	06	30	115	10	00	74	Location see Condon (1967, Fig. 78)
Jimba Jimba Calcarenite Member	Jimba Jimba Station (KENNEDY RANGE)	Northeast side of Jimba Syncline 16 km west of Jimba Jimba homestead	25	51	30	115	34	30	44	Location see Condon (1967, Fig. 89)
Keogh Formation	Keogh Hill (GLENBURGH)	7 km east of Callytharra Spring, at Keogh Hill	25	51	30	115	34	30	44	Location see Condon (1967, Fig. 89)
BYRO GROUP	Byro station (BYRO)									
Coyrie Formation	Coyrie paddock, Williambury Station (KENNEDY RANGE)	Between Toby Bore and Red Monkey Bore, Moogooree Station	24 to 24	06 05	20 20	115 115	09 07	30 30	186	Consists of 3 partial sections (Condon, 1967, Fig. 78)
Mallens Sandstone	Mallens paddock, Williambury Station (KENNEDY RANGE)	2 km southwest of Red Monkey Bore	24 to 24	04 05	40 30	115 115	07 06	10 30	150	Location see Condon (1967, Fig. 78)
Bulgadoo Shale	Bulgadoo Pool, Minilya River (WINNING POOL)	Midway between Coolkilya Pool and Wandagee homestead	23 to 23	44 44	40 50	114 114	30 28	30 50	154	Location see Condon (1967, Fig. 108)
Cundlego Formation	Cundlego Crossing Minilya River (WINNING POOL)	Midway between Coolkilya Pool and Wandagee homestead	23 to 23	45 45	20 40	114 114	28 28	50 00	332	Location see Condon (1967, Fig. 108)
Quinnanie Shale	Quinnanie Corner, Wandagee Station (WINNING POOL)	Coolkilya Pool, Minilya River	23	44	10	114	25	20	135	Location of Quinnanie corner uncertain. Location of section see Condon (1967, Fig. 126)
Wandagee Formation	Wandagee Station (WINNING POOL)	Coolkilya Pool, Minilya River	23 to 23	44 44	20 40	114 114	25 24	20 40	173	Location see Condon (1967, Fig. 126)
Nalbia Sandstone	Nalbia paddock, Wandagee Station (WINNING POOL)	Approx. 4 km north of Wandagee Hill	23	48	10	114	25	10	40	Section very poor (see text)
Baker Formation	Baker's Bore, Middalya Station (KENNEDY RANGE)	Blackheart Creek, Middalya Station	24 to 24	13 14	00 20	115 115	02 03	50 00	53	Location see Condon (1967, Fig. 130)
		EARLY AND LATE PERMIAN								
KENNEDY GROUP	Kennedy Range (KENNEDY RANGE)									
Coolkilya Sandstone	Coolkilya paddock, Wandagee Station (WINNING POOL)	Wandagee Hill, lower part, east face	23	50	10	114	25	49	116	Paddock now spelt Koolkilya. Location of section see Condon (1967, Fig. 137)
Mungadan Sandstone	Mungadan paddock, Wandagee Station (WINNING POOL)	Wandagee Hill, upper part, east face	23	50	10	114	25	50	36	Location see Condon (1967, Fig. 137)
Binthalya Formation	Binthalya Station (KENNEDY RANGE)	Immediately east of Venny Peak	24 to 24	50 49	00 30	114 114	56 57	50 30	544	Erosional top. Location see Condon (1967, Fig. 142)

TABLE 2. TYPE SECTION DATA (continued)

Name of unit	*Derivation of name*	*Type locality*	*Type section coordinates* *Latitude (S)* D M S	*Longitude (E)* D M S	*Thickness (m)*	*Comments*
		LATE PERMIAN AND TRIASSIC				
Chinty Formation	Chinty Creek (ONSLOW)	Onslow 1, 2096–2258 m	21 45 17	114 52 17	162	Does not outcrop
Locker Shale	Locker Point (ONSLOW)	Onslow 1, 1587–2096 m	21 45 17	114 52 17	509	Does not outcrop
Cunaloo Member	Cunaloo 1 (YANREY)	Cunaloo 1, 534–548.6 m	22 00 48	114 53 47	14.6	Does not outcrop
Mungaroo Formation	Mungaroo Well, Minderoo Station (ONSLOW)	Long Island 1, 749–1992 m	21 37 10	114 41 10	1198	Does not outcrop
Wittecarra Sandstone	Wittecarra Gully (AJANA)	Nancy Beach/Shell House, south of Kalbarri	27 48 10	114 07 00	8	
Kockatea Shale	Kockatea Gully (GERALDTON)	Near junction of Kockatea Gully and Greenough River	23 33 10	115 10 10	12.5	
		JURASSIC				
Woodleigh Formation	Woodleigh Station (YARINGA)	Woodleigh No. 7, 210–235 m	26 07 30	114 45 00	25	Base of unit not penetrated
Dingo Claystone	Dingo Well, Exmouth Gulf Station (YANREY)	Cape Range 2, 1130–4624 m	22 05 57	113 59 32	3494	Named after Dingo Well. Base not penetrated in type section
Learmonth Formation	Learmonth Airfield (YANREY)	Rough Range 1, 1216–1890 m	22 25 06	114 04 55	674	
Biggada Formation	Biggada Creek (BARROW IS.)	Barrow Deep 1, 3229–3617 m	20 50 07	115 22 56	388	
Dupuy Formation	Cape Dupuy (BARROW IS.)	Barrow 25, 2047–2487 m	20 40 22	115 26 24	440	
Legendre Formation	Legendre Island (DAMPIER)	Rosemary 1, 3284–3909 m	19 57 16	116 20 41	625	Base of unit not penetrated
Angel Formation	Angel Island (DAMPIER)	Angel 1, 2655–3167 m	19 30 20	116 35 48	512	Base of unit not penetrated
		EARLY AND LATE CRETACEOUS				
BARROW GROUP	Barrow Island (BARROW IS.)					
Malouet Formation	Cape Malouet (BARROW IS.)	Barrow 1, 1370–1986 m	20 49 06	115 23 38	616	
Flacourt Formation	Flacourt Bay (BARROW IS.)	Barrow 1, 914–1370 m	20 49 06	115 23 38	456	

UNGROUPED UNITS											
Wogatti Sandstone	Wogatti Well, Exmouth Gulf Station (YANREY)	Rough Range 1, 1109–1216 m	22	25	06	114	04	55	107	
Yarraloola Conglomerate	Yarralooia Station (YARRALOOLA)	11 km southeast of Yarraloola homestead	21	37	30	115	57	10	<3	
Nanutarra Formation	Nanutarra Station (YANREY)	8 km north of "The Range" homestead	22	14	00	115	28	30	25	The Range homestead is outcamp for Nanutarra Station
Peepingee Greensand Member	Peepingee Creek (YANREY)	Tabletop Hills	22	18	05	115	15	05	11	
WINNING GROUP	Winning Station (WINNING POOL)									
Birdrong Sandstone	Birdrong Spring (KENNEDY RANGE)	1 km south of Birdrong Spring	24	14	55	114	49	55	33	Location see Condon (1968, Fig. 148)
Muderong Shale	Muderong Bore, Middalya (KENNEDY RANGE)	In butte 3 km southwest of Muderong Bore	24	08	05	114	45	50	12	Muderong Bore now called Twin Bores. Location see Condon (1968, Fig. 149)
Mardie Greensand Member	Mardie Pool, Mardie Station	Mardie 1, 160–172 m	21	21	14	115	42	23	12	
Windalia Sand Member	Windalia Hill (WINNING POOL)	Barrow 1, 644–674.5 m	20	49	02	115	23	02	34.5	
Windalia Radiolarite	Windalia Hill (WINNING POOL)	Windalia Hill	23	16	10	114	47	10	36	Stratigraphic top not preserved
Haycock Marl	Haycock 1 (DAMPIER)	Goodwyn 6, 2642–2738 m	19	43	24	115	51	12	96	Well named after Haycock Island
Gearle Siltstone	Gearle paddock, Cardabia Station (YANREY)	C-Y Creek	22 to 22	54 53	20 00	114 114	09 08	30 50	—	Poorly exposed except uppermost part, base not exposed
Alinga Formation	Alinga Point (AJANA)	Alinga Point	27	42	30	114	09	40	15	
		LATE CRETACEOUS								
UNGROUPED UNITS										
Toolonga Calcilutite	Toolonga Hill (AJANA)	2 km northeast of Yalthoo Bore	27	36	00	114	13	40	26	Eroded top to section
Withnell Formation	Withnell 1	Goodwyn 6, 2469–2602 m	19	43	24	115	51	12	133	Well named after Withnell Bay
Korojon Calcarenite	Korojon Pool, Cardabia Creek (YANREY)	C-Y Creek	22 to 22	53 52	20 40	114 114	07 07	40 00	38	Thickness doubtful—see text
Miria Formation	Miria paddock (WINNING POOL)	Toothawarra Creek, Cardabia	22	49	40	114	09	00	1.2	Section adjoins Cardabia Calcarenite type section

TABLE 2. TYPE SECTION DATA (continued)

Name of unit	*Derivation of name*	*Type locality*	*Type section coordinates* *Latitude (S)* D M S	*Longitude (E)* D M S	*Thickness (m)*	*Comments*
		PALEOCENE AND EARLY EOCENE				
Lambert Formation	Lambert 1	Lambert 1, 2449–2502 m	19 27 23	116 29 23	53	Well named after Cape Lambert. Upper part of formation expressed best in Miller 1, 2580–2591 m
Cardabia Calcarenite	Cardabia Station (MINILYA)	Toothawarra Creek	22 49 40 to 22 49 00	114 09 00 114 07 40	77	Low dips render thickness unreliable
Boongerooda Greensand Member	Boongerooda Clay Hole (YANREY)	Toothawarra Creek	22 49 40	114 09 00	3	
Wadera Member	Wadera paddock (MINILYA)	Toothawarra Creek			23	Within Cardabia Calcarenite type section
Pirie Member	Pirie paddock (YANREY)	Toothawarra Creek			29.5	Within Cardabia Calcarenite type section
Cashin Member	Cashin paddock (WINNING POOL)	Toothawarra Creek			8.5	Within Cardabia Calcarenite type section
Jubilee Member	Jubilee Well (YANREY)	Creek 1 km south Giralia–Bullara road	22 40 70 to 22 40 00	114 11 40 114 11 20	10.7	
Dockrell Formation	Dockrell 1	Dockrell 1, 2376–2555 m	19 47 17	115 46 47	179	Well named after Dockrell Reef
Wilcox Formation	Wilcox 1	Goodwyn 6, 2132–2292 m	19 43 24	115 51 12	160	Well named after Wilcox Island
		EOCENE				
Walcott Formation	Walcott 1	Goodwyn 6, 2061–2132 m	19 43 24	115 51 12	71	Well named after Walcott Island. Upper part of formation developed best in Fisher 1, 2109–2185 m
Giralia Calcarenite	Giralia Station (YANREY)	Along creek near No. 10 bore, Cardabia	22 55 50 to 22 55 30	114 03 30 114 01 10	61	
Merlinleigh Sandstone	Merlinleigh Station (KENNEDY RANGE)	About 1 km southeast of Merlinleigh homestead, in mesa	24 19 20	115 12 00	7	

Robe Pisolite	Robe River (YARRALOOLA)	6m east-southeast from Deepdale homestead in north face of mesa	21	43	50	116	14	30	15	South side, Robe River
OLIGOCENE AND MIOCENE										
Pindilya Formation	Pindilya Bore (GLENBURGH)	Between Salt Well and Swelt Bore, Curbur	26	22	40	115	47	20	2.8	Intensely silcreted
CAPE RANGE GROUP	Cape Range (NINGALOO/YANREY)									
Mandu Calcarenite	Mandu Mandu Creek (NINGALOO)	Badjirrajirra Creek, Cape Range	22	06	10	114	02	00	76	Base not exposed
Bullara Limestone	Bullara Station (YANREY)	Rough Range South 1, 220–306 m	22	37	21	113	57	43	186	Not exposed
Tulki Limestone	Tulki Well, Cape Range area (NINGALOO)	Badjirrajirra Creek, Cape Range	22	06	00	114	02	50	95	Remeasured thickness
Trealla Limestone	Mount Trealla (original name of Mount Lefroy) (YANREY)	Northeast face, Mount Lefroy	22	13	00	114	00	20	48	
Lamont Sandstone	Lamont Well, Giralia (YANREY)	2.4 km northeast of Lamont Well	22	45	00	114	17	20	3.3	No stratigraphic top
Pilgramunna Formation	Pilgramunna Creek (NINGALOO)	South bank, mouth of Yardie Creek	22	20	10	113	49	40	30	
Vlaming Sandstone	Vlaming Head (ONSLOW)	1.6 km south-southeast of Tulki Well	22	06	30	113	54	20	38	
Bare Formation	Bare Rock (DAMPIER)	Goodwyn 6, 712–1120 m	19	43	24	115	51	12	408	
PLIOCENE AND QUATERNARY										
UNGROUPED UNITS										
Delambre Formation	Delambre 1	Fisher 1, 405–945 m	19	49	25	115	42	32	>540	
Exmouth Sandstone	Exmouth Gulf (ONSLOW/YANREY)	East side, Unknown Hill	22	21		114	00		40	Details from Condon and others (1955)
Muiron Member	Muiron Islands (ONSLOW)	Southeast of Tulki Well	22	06	30	113	54	00	<25	About 150 m north-northwest of Vlaming Sandstone type section
Milyering Member	Milyering Well (NINGALOO)	Southeast of Tulki Well	22	06	20	113	53	50	<30	About 400 m north-northwest of Vlaming Sandstone type section

TABLE 2. TYPE SECTION DATA (continued)

Name of unit	*Derivation of name*	*Type locality*	*Type section coordinates*						*Thickness (m)*	*Comments*
			Latitude (S)			*Longitude (E)*				
			D	*M*	*S*	*D*	*M*	*S*		
PLIOCENE AND QUATERNARY (continued)										
Bundera Calcarenite	Bundera Well (NINGALOO)	Large sinkhole 1 km northwest of Bundera Well	22	24	30	113	45	40	4	Only Tantabiddi Member exposed
Jurabi Member	Jurabi Point (ONSLOW)	About 1 km south of Tulki Well	22	06	20	113	53	40	<20	About 800 m north-northwest of Vlaming Sandstone type location
Tantabiddi Member	Tantabiddi Well (ONSLOW)	5 km southwest of Vlaming Head	21	50	10	114	04	20	<20	In sinkhole 100 m south of track
Mowbowra Conglomerate Member	Mowbowra Well (ONSLOW)	Mouth of Mowbowra Creek	22	00	10	114	07	30	8	
Peron Sandstone	Cape Peron North (SHARK BAY)	Cape Peron North	25	30	30	113	30	30	<100	Previously termed "Cape Peron". Base not exposed
Tamala Limestone	Tamala Station (EDEL)	Zuytdorp Cliffs at Womerangee Hill	26	54	20	113	45	50	251	Base not exposed
Dampier Limestone	Dampier Road (anchorage) (SHARK BAY)	5 km south-southwest of Cape Peron North	25	32	30	113	29	20	<10	
Carbla Oolite Member	Carbla Point (YARINGA)	Goat Point, Carbla Station	26	20	00	114	13	30	<20	
Bibra Limestone	Bibra Landing (WOORAMEL)	Gladstone Embayment	25	57		114	15		<10	Location approximate
Depuch Formation	Depuch Loop (EDEL)	None specified							<1	
Walatharra Formation	Walatharra paddock (YANREY)	11 km west of Giralia homestead	22	42	00	114	15	50	30	
Nadarra Formation	Nadarra Well (WINNING POOL)	12.5 km northeast of Williambury homestead	23	48	00	115	14	40	18	Thickness in type locality very variable
Hamelin Coquina	Hamelin Station (YARINGA)	None specified							<10	

TABLE 3. GAZETTEER OF LOCALITIES MENTIONED IN TEXT

Locality	*Sheet*	*Latitude (S)*			*Longitude (E)*		
		D	*M*	*S*	*D*	*M*	*S*
Alinga Point	AJANA	27	38	10	114	10	10
Alison Well, Lyons River	KENNEDY RANGE	24	41	00	115	24	40
Angel Island	DAMPIER	20	30	00	116	47	50
Arthur River outcamp, Eudamullah	MOUNT PHILLIPS	24	42	30	115	44	40
Austin Well, Lyons River	KENNEDY RANGE	24	28	40	115	22	20
Badjirrajirra Creek	KENNEDY RANGE	22	06	00	114	02	30
Bakers Bore, Middalya	KENNEDY RANGE	24	07	50	114	55	20
Balla wheat bins	GERALDTON	28	01	40	114	59	00
Balline homestead	GERALDTON	28	00	10	114	13	00
Ballythanna Hill	BYRO	26	03	30	115	39	50
Bare Rock	DAMPIER	20	33	10	116	26	30
Barrow Island	BARROW ISLAND	20	45		115	43	
Bejaling Beach Ridges	QUOBBA	24	45	00	113	38	50
Bellefin Prong	EDEL	26	10	40	113	18	00
Bibbawarra Bore	QUOBBA	24	45	50	113	42	50
Bernier Island	QUOBBA	24	50		113	07	
Bibra Landing (position approx.)	WOORAMEL	25	56		114	15	
Bidgemia homestead	WOORAMEL	25	02	40	115	18	20
Biggada Creek	BARROW ISLAND	20	47	00	115	21	40
Billidee Well, Moogooree	KENNEDY RANGE	24	08	10	115	08	50
Bilung Creek	GLENBURGH	25	43	10	115	54	40
Bilung Pool	GLENBURGH	25	42	20	115	59	20
Bindoo Hill	GERALDTON	28	29	40	115	14	20
Binnu	GERALDTON	28	02	30	114	40	20
Binthabooka Bore, Lyons River	KENNEDY RANGE	24	45	00	115	11	50
Binthabooka Creek	KENNEDY RANGE	24	40	00	115	16	20
Binthalya homestead	KENNEDY RANGE	24	41	30	114	50	10
Binthalya Spring	KENNEDY RANGE	24	46	30	114	56	30
Birdrong Spring	KENNEDY RANGE	24	14	30	114	50	40
Black Dam, Cardabia	WINNING POOL	23	06	10	114	10	00
Blackheart Creek	KENNEDY RANGE	24	11	00	115	01	00
Bompas Hill	AJANA	27	17	10	115	19	10
Boonaberrie Bore, Bidgemia	WOORAMEL	25	08	10	115	32	40
Boongerooda Clay Hole (position approx.)	YANREY	22	53	00	114	01	40
Brickhouse 1	KENNEDY RANGE	24	51	40	114	01	50
Brickhouse 4	SHARK BAY	25	11	10	113	53	30
Broadhurst Bight	SHARK BAY	25	32	40	113	28	50
Bulgadoo Pool	WINNING POOL	23	44	30	114	30	40
Bullara homestead	YANREY	22	40	40	114	02	10
Bundera Well	NINGALOO	22	24	40	113	46	20
Burraboogatta Peninsula	EDEL	26	30	00	113	37	30
Byro homestead	BYRO	26	04	50	116	09	10
Callytharra Spring	GLENBURGH	25	52	20	115	00	30
Cape Cuvier	QUOBBA	24	13	30	113	23	20
Cape Lambert	ROEBOURNE	20	35	40	117	10	10
Cape Dupuy	BARROW ISLAND	20	40	00	115	26	10
Cape Malouet	BARROW ISLAND	20	42	50	115	23	40
Cape Peron North	SHARK BAY	25	30	30	113	30	30
Cape Range	NINGALOO/YANREY	22			114		
Carbla homestead	YARINGA	26	12	10	114	17	20
Carbla Point	YARINGA	26	15	50	114	13	00
Cardabia Creek	QUOBBA	24	35	20	113	45	00
Cardabia Creek	YANREY/WINNING POOL	23	06	50	114	10	30
Cardabia homestead	MINILYA	23	06	20	113	47	50
Cardabia No. 10 Bore	YANREY	22	55	30	114	02	00
Cardigo Bore, Mia Mia	WINNING POOL	23	15	40	114	30	50
Carnarvon	QUOBBA	24	52		113	39	

TABLE 3. GAZETTEER OF LOCALITIES MENTIONED TEXT (continued).

Locality	*Sheet*	*Latitude (S)*			*Longitude (E)*		
		D	*M*	*S*	*D*	*M*	*S*
Carrandibby Range	GLENBURGH	25	46		115	36	
Carrarang Peninsula	EDEL	26	20	00	113	31	40
Cashin Paddock, Cardabia	WINNING POOL	23	09		114	01	
Centenary Bore, Cardabia	NINGALOO	22	59	00	113	58	40
Chinkia Creek	WINNING POOL	23	23	10	114	12	30
Chinty Creek	ONSLOW	21	53	20	114	50	10
Congo Pool	GLENBURGH	25	23	20	115	53	00
Coolkilya Paddock, Wandagee	WINNING POOL	23	45		114	24	
Coolkilya Pool	WINNING POOL	23	44	00	114	25	10
Coolyun Hill	BYRO	26	11	50	115	48	30
Coolyun Well	BYRO	26	12	00	115	49	10
Coonantha Well, Bidgemia	KENNEDY RANGE	24	51	20	115	22	40
Coondoo outcamp	MOUNT PHILLIPS	24	49	00	115	34	30
Cooralya homestead	KENNEDY RANGE	24	26	50	114	04	40
Coordewandy homestead (ruins)	GLENBURGH	25	35	40	115	58	10
Cordalia Well, Mia Mia	WINNING POOL	23	25	20	114	39	50
Corktree Well, Eudamullah	MOUNT PHILLIPS	24	39	40	115	43	00
Cream Creek	MOUNT PHILLIPS	24	33		115	40	
Corktree Well, Muggon	YARINGA	26	34	20	115	26	10
Coyrie Paddock, Williambury	KENNEDY RANGE	24	07		115	09	
Cundlego Crossing	WINNING POOL	23	44	50	114	27	30
Curbur homestead	BYRO	26	28	00	115	56	10
C-Y Creek	YANREY	22	50	40	114	04	20
Dairy Creek homestead	GLENBURGH	25	16	40	115	51	40
Dampier	DAMPIER	20	41		116	41	
Dampier Road (anchorage)	SHARK BAY	25	32		113	27	
Deep Pool	WOORAMEL	25	41	40	114	58	50
Deep Well, Lyons River	MOUNT PHILLIPS	24	38	10	115	30	00
Deep Well, Uaroo	YANREY	22	45	30	115	12	00
Deepdale homestead	YARRALOOLA	21	42	50	116	11	00
Denham	SHARK BAY	25	55	50	113	32	10
Depuch Inlet	EDEL	26	28	50	113	35	20
Dingo Well, Exmouth Gulf	YANREY	22	25	40	114	00	50
Dirk Hartog Island	SHARK BAY	25	43		112	55	
Dockrell Reef	DAMPIER	20	39	40	116	31	10
Donnellys Well, Moogooree	KENNEDY RANGE	24	04	20	115	04	40
Dorre Island	SHARK BAY	25	08		113	06	
Dubout Point	BARROW ISLAND	25	53	00	113	45	40
Durrabiddy Well	GLENBURGH	25	23	10	115	40	00
Earilier Hill	GLENBURGH	25	59	50	116	03	10
Ebra Bore, Lyndon	WINNING POOL	23	35	30	115	05	20
Exmouth	ONSLOW	21	56	00	114	07	30
Exmouth Gulf	ONSLOW/YANREY	22			114	20	
Exmouth Gulf homestead	YANREY	22	22	40	114	06	20
Faure Island	SHARK BAY	25	53		113	52	
Faure Sill	SHARK BAY/YARINGA	25	57		114	00	
Flacourt Bay	BARROW ISLAND	20	44	50	115	22	00
Fletchers Well, Dairy Creek	WOORAMEL	25	21	40	115	27	20
Fossil Hill	GLENBURGH	25	03	20	115	33	20
Four Corners Bore, Mia Mia	WINNING POOL	23	20	30	114	31	40
Garries Lagoon	YARINGA	26	22	30	115	13	30
Gascoyne Junction	WOORAMEL	25	03	10	115	12	20
Gearle Paddock, Cardabia	WINNING POOL	23	02	30	114	11	00
Gee Gie outcamp	AJANA	27	21	00	114	08	40
Geraldton	GERALDTON	28	46		113	35	
Giralia homestead	YANREY	22	41	20	114	22	00
Giralia Range	YANREY/WINNING POOL	23	04		114	03	
Gladstone Embayment	WOORAMEL	25	58	30	114	14	00
Gnaraloo homestead	MINILYA	23	49	30	113	31	10
Gneudna Paddock, Williambury	WINNING POOL	23	58		115	14	

TABLE 3. GAZETTEER OF LOCALITIES MENTIONED TEXT (continued).

Locality	*Sheet*	*Latitude (S)*			*Longitude (E)*		
		D	*M*	*S*	*D*	*M*	*S*
Gneudna Well, Williambury	WINNING POOL	23	55	30	115	12	50
Goat Point, Hamelin Pool	YARINGA	26	20	00	114	13	30
Golaluarra Brook	GERALDTON	28	44	30	114	55	00
Gooch Range	WINNING POOL	23	41		114	47	
Goulet Bluff	EDEL	26	13	10	113	41	20
Gregory	GERALDTON	28	10	40	114	14	20
Greys Creek	KENNEDY RANGE	24	49	30	115	23	40
Gubbiddy Well, Eudamullah	MOUNT PHILLIPS	24	54	30	115	40	30
Hamelin homestead	YARINGA	26	26	00	114	11	10
Hamelin Pool	YARINGA	26	10		114	05	
Harris Well, Williambury (now bore)	WINNING POOL	23	51	20	115	04	40
Haycock Island	DAMPIER	20	40	00	116	37	30
Heirisson Prong	EDEL	26	03	20	113	21	40
Houtman Abrolhos	GERALDTON	28	35		113	45	
Howell Bore, Mount Sandiman	KENNEDY RANGE	24	13	40	115	20	40
Hutton Creek	KENNEDY RANGE	24	05	30	114	20	40
Indialla Spring	GERALDTON	28	31	30	114	53	00
Jimba Jimba homestead	WOORAMEL	25	02	50	115	08	00
Jubilee Bore, Giralia (now well)	YANREY	22	36	10	114	12	40
Jundelaya Hill	YANREY	22	34	00	115	23	00
Jurabi Point	ONSLOW	21	52	30	113	59	40
Kalbarri	AJANA	27	42	30	114	10	10
Karrajong Dam	WINNING POOL	23	15	10	114	13	20
Karratha	DAMPIER	20	44		116	51	
Karrilla Well, Middalya	WINNING POOL	23	52	30	114	54	50
Kennedy Bore, Middalya	KENNEDY RANGE	24	12	20	115	01	10
Kennedy Range	KENNEDY RANGE	24	30		115		
Keogh Hill	GLENBURGH	25	51	30	115	34	40
Kockatea Gully	GERALDTON	28	32	30	115	11	10
Kopke Point	WOORAMEL	25	59	20	114	11	40
Korojon Pool	WINNING POOL	23	19	10	114	04	40
Lake Brebrele	BYRO	26	19	40	115	57	50
Lake Coolcurdoo	AJANA	27	25	10	114	08	20
Lake MacLeod	MINILYA/QUOBBA	23	50		113	45	
Lake Nerramyne	AJANA	27	47	40	115	25	30
Lamont Well, Giralia	YANREY	22	45	40	114	16	10
Learmonth Airfield	YANREY	22	14	00	114	05	20
Legendre Island	DAMPIER	20	22	20	116	51	10
Lharidon Bight	EDEL	26	05		113	45	
Locker Point	ONSLOW	21	48	10	114	43	20
Lockwood Springs	AJANA	27	46	50	114	27	20
Long Island (Serrurier Island)	ONSLOW	21	36	50	114	41	00
Lyndon homestead	WINNING POOL	23	38	10	115	15	30
Lyons River homestead	KENNEDY RANGE	24	37	50	115	20	20
Mallens Paddock, Williambury	KENNEDY RANGE	24	03		115	02	
Mandu Mandu Creek	NINGALOO	22	09	10	113	55	12
Mardathuna homestead	KENNEDY RANGE	24	28	40	114	33	20
Mardie Pool	YARRALOOLA	21	11	00	115	52	40
Mauds Landing Bore, Cardabia	MINILYA	23	06	00	113	56	30
Meads Bore, Mount Sandiman	KENNEDY RANGE	24	30	40	115	15	10
Meanarra Hill	AJANA	27	41	50	114	13	20
Merlinleigh homestead (ruins)	KENNEDY RANGE	24	18	50	115	11	10
Merrebello Pool	WINNING POOL	23	20	58	114	14	50
Mia Mia homestead	WINNING POOL	23	23	10	114	26	10
Mia Mia shearing sheds (top sheds)	WINNING POOL	23	30	50	114	42	10
Middalya homestead	WINNING POOL	23	54	30	115	46	00
Miller Bore, Mount Sandiman	KENNEDY RANGE	24	28	10	115	18	40
Milyering Well	NINGALOO	22	01	10	113	55	50
Miria paddock, Cardabia	WINNING POOL	23	12		114	10	

TABLE 3. GAZETTEER OF LOCALITIES MENTIONED TEXT (continued).

Locality	*Sheet*	*Latitude (S)*			*Longitude (E)*		
		D	*M*	*S*	*D*	*M*	*S*
Mitta Mitta Bore, Mount Sandiman	KENNEDY RANGE	24	25	10	115	14	10
Modesty Villa outcamp	AJANA	27	22	40	114	07	50
Montebello Islands	BARROW ISLAND	20	26		115	30	
Moogooloo Hill	WINNING POOL	23	36	00	114	44	20
Moogooree homestead	KENNEDY RANGE	24	03	50	115	12	10
Mooka homestead	KENNEDY RANGE	24	57	50	114	48	30
Mount Fisher	ROEBOURNE	20	55	10	117	27	40
Mount Lefroy	YANREY	22	13	00	114	00	20
Mount Madeline	GLENBURGH	25	44	30	115	40	30
Mount Minchin	GERALDTON	28	15	30	114	29	00
Mount Rebecca	BYRO	26	05	35	116	00	00
Mount Sandiman homestead	KENNEDY RANGE	24	24	50	115	23	30
Mount Sandiman shearing sheds	KENNEDY RANGE	24	23	50	115	16	40
Mowbowra Creek	ONSLOW	21	59	10	114	05	20
Mowbowra Well	ONSLOW	21	59	40	114	07	20
Muderong Bore (now called Twin Bores), Middalya	KENNEDY RANGE	24	07	30	114	47	10
Muggon homestead	BYRO	26	37	00	115	32	40
Mulyajingle Peak	BYRO	26	10	10	115	57	30
Munaballya Tank	KENNEDY RANGE	24	06	00	115	22	30
Munabia paddock, Williambury	WINNING POOL	23	48		115	12	
Mundarrie Well, Middalya	WINNING POOL	23	54	20	114	55	50
Mungadan paddock, Wandagee	WINNING POOL	23	50		114	27	
Mungaroo Well, Minderoo	ONSLOW	21	55	20	115	02	00
Murchison House homestead	AJANA	27	38	50	114	14	10
Murray Peak	BYRO	26	04	10	115	39	30
Nabawa	GERALDTON	28	30	00	114	47	20
Nadarra Well (now Bore)	WINNING POOL	23	51	10	115	13	10
Nalbia paddock, Wandagee	WINNING POOL	23	50	20	114	32	00
Nancy Beach (Shell House)	AJANA	27	48	10	114	07	00
Nannyarra paddock, Moogooree	KENNEDY RANGE	24	10	00	115	18	20
Nanutarra homestead	YANREY/WYLOO	22	32	40	115	30	00
Nanyingee Hill	YANREY	22	26	50	115	12	10
NMF 575 (hill)	WINNING POOL	23	51	10	114	49	00
No. 22 Well, Dairy Creek	GLENBURGH	25	23	20	115	39	40
Nolba	GERALDTON	28	21	50	114	52	30
Northampton	GERALDTON	28	21	00	114	37	40
North Muiron Island	ONSLOW	21	38	30	114	22	00
North West Cape	ONSLOW	21	47	20	114	09	50
Northern Gully	GERALDTON	28	42	30	114	54	20
Nyarra Creek	WOORAMEL	25	45	00	115	25	30
Onslow	ONSLOW	21	38	20	115	06	50
Paddys outcamp, Middalya	KENNEDY RANGE	24	05	10	114	42	40
Parry Range	WYLOO	22	20		115	32	
Pasco Island	BARROW ISLAND	20	57	40	115	20	20
Pats Dam, Muggon	YARINGA	26	22	50	115	27	50
Peepingee Creek	YANREY	22	23	50	115	18	40
Pells Range	WOORAMEL	25	15		115	28	
Pencell Pool	AJANA	27	37	50	114	48	10
Peron Peninsula	EDEL/SHARK BAY	25	50		113	35	
Petit Point	SHARK BAY	25	56	40	113	52	20
Pilgramunna Creek	NINGALOO	22	11	50	113	50	40
Pindilya Bore, Byro	GLENBURGH	25	57	30	115	45	50
Pirie paddock, Cardabia	YANREY	22	57		114	05	
Plant Well, Coordewandy	GLENBURGH	25	33	50	115	52	10
Pleiades Tank, Mia Mia	WINNING POOL	23	34	30	114	46	30
Point Maud	MINILYA	23	07	20	113	45	40
Point Sweeney Mia	YARINGA	26	18	10	114	13	30
Port Hedland	PORT HEDLAND	20	19		118	36	
Port Walcott	ROEBOURNE	20	39	10	117	11	30

TABLE 3. GAZETTEER OF LOCALITIES MENTIONED TEXT (continued).

Locality	*Sheet*	*Latitude (S)*			*Longitude (E)*		
		D	*M*	*S*	*D*	*M*	*S*
Quail Springs	WINNING POOL	23	39		115	11	
Quobba homestead	QUOBBA	24	24	00	113	24	10
Range Bore, Lyons River	KENNEDY RANGE	24	48	00	115	10	50
Red Bluff	AJANA	27	44	50	114	08	20
Red Hill	AJANA	27	40	10	114	10	50
Red Monkey Bore, Moogooree	KENNEDY RANGE	24	04	20	115	08	00
Red Ochre Bore, Dairy Creek	GLENBURGH	25	19	20	115	51	50
Remarkable Hill	WINNING POOL	23	01	50	114	05	10
Rocky Pool	KENNEDY RANGE	24	45	30	114	08	00
Rosemary Island	DAMPIER	20	28	30	116	35	00
Rough Range	YANREY	22	25	20	114	04	00
Round Hill	WINNING POOL	23	21	00	114	39	40
Round Hill Well, Winning	WINNING POOL	23	22	30	114	39	30
Salt Well, Curbur	BYRO	26	25	00	115	48	20
Salt Well, Eudamullah	MOUNT PHILLIPS	24	38		115	42	45
Satellite Bore, Mia Mia	WINNING POOL	23	17	20	114	33	20
Second Gully	AJANA	27	37	30	114	11	30
Shark Bay		25	20		113	30	
Shell House (Nancy Beach)	AJANA	27	48	10	114	07	00
Snake Well, Eudamullah	MOUNT PHILLIPS	24	37	00	115	39	50
South Branch Bore, Williambury	WINNING POOL	23	57	30	115	07	40
South Lyndon Wells, Minilya	WINNING POOL	23	29	20	114	16	00
Southern Cross Bore, Middalya	KENNEDY RANGE	24	06	30	114	49	50
Steads Bore, Eudamullah	MOUNT PHILLIPS	24	34	20	115	36	50
Stone Wall	AJANA	27	35	00	114	15	00
Sugarloaf Hill	GERALDTON	28	16	20	114	44	30
Sugarloaf Hill	YARRALOOLA	21	37	30	115	57	10
Swelt Bore, Curbur	BYRO	26	22	39	115	47	24
Tabletop Hills	YANREY	22	27	00	115	22	30
Taffs Bore, Yalbalgo	WOORAMEL	25	14	20	114	48	20
Tailifer Isthmus	EDEL	26	11	30	113	42	00
Tamala homestead	EDEL	26	41	50	113	42	40
Tantabiddi Well	ONSLOW	21	56	20	113	58	00
The Loop	AJANA	27	32	40	114	27	30
The Range homestead	YANREY	22	16	10	115	21	40
Toby Bore, Moogooree	KENNEDY RANGE	24	06	10	115	10	00
Toolonga Hill	AJANA	27	34	20	114	15	00
Toothawarra Creek	YANREY	22	48	50	114	07	20
Top Burraboogatta Well	EDEL	26	31	30	113	36	00
Towera homestead	WINNING POOL	23	10	30	115	07	00
Tulki Well	NINGALOO	22	05	30	113	53	50
Tumblagooda Hill	AJANA	27	40	20	114	09	50
Twin Beds (Muderong Bore), Middalya	KENNEDY RANGE	24	07	30	114	47	10
Unknown Hill	NINGALOO	22	21	00	113	59	30
Useless Loop	EDEL	26	07	40	113	24	40
Venny Peak	KENNEDY RANGE	24	49	50	114	56	30
Vlaming Head	ONSLOW	21	48	20	114	06	20
Wadera paddock, Cardabia	MINILYA	23	00		114	00	
Waggine Spring	GERALDTON	28	20	40	114	52	40
Walatharra paddock, Giralia	YANREY	22	38		114	13	
Walcott Island	DAMPIER	20	39	40	116	57	30
Walter Well, Towera	WINNING POOL	23	20	10	115	01	20
Wandagee Hill	WINNING POOL	23	50	10	114	27	00
Wandagee homestead	WINNING POOL	23	46	00	114	33	00
Watermelon Spring and Creek	KENNEDY RANGE	24	21	00	114	54	10
Wicherina	GERALDTON	28	43	10	115	00	20
Wilcox Island	DAMPIER	20	27	00	116	50	20

TABLE 3. GAZETTEER OF LOCALITIES MENTIONED TEXT (continued).

Locality	*Sheet*	*Latitude (S)*			*Longitude (E)*		
		D	*M*	*S*	*D*	*M*	*S*
Willaraddie Creek	WINNING POOL	23	49	20	115	14	40
Williambury homestead	WINNING POOL	23	52	00	115	08	40
Windalia Hill	WINNING POOL	23	16	10	114	47	10
Winning homestead	WINNING POOL	23	09	30	114	32	20
Withnell Bay	DAMPIER	20	34	50	116	46	40
Wittecarra Gully	AJANA	27	44	40	114	09	10
Wogatti Well, Exmouth Gulf	YANREY	22	19	40	114	03	20
Wolgangie Bore, Mount Sandiman	KENNEDY RANGE	24	14	30	115	16	30
Womerangee Hill	EDEL	26	54	20	113	46	50
Wongong Well, Muggon/Curbur	BYRO	26	28	20	115	32	00
Woodcock Bore, Mount Sandiman	KENNEDY RANGE	24	18	30	115	20	30
Woodleigh homestead (old Woodleigh)	YARINGA	26	11	30	114	33	10
Woodleigh No. 2 Bore (old)	YARINGA	26	03	00	114	45	30
Woodleigh No. 7 Bore	YARINGA	26	07	40	114	45	10
Wooramel homestead	WOORAMEL	25	44	30	114	17	00
Yabaroo Bore, Mount Sandiman	KENNEDY RANGE	24	16	40	115	17	00
Yalbalgo homestead	WOORAMEL	25	11	30	114	4n0	50
Yalbalgo No. 9 Bore	WOORAMEL	25	16	00	114	45	20
Yalthoo Bore, Murchison House	AJANA	27	36	30	114	13	00
Yardie Creek	NINGALOO	22	20	20	113	49	00
Yaringa homestead	WOORAMEL	25	56	50	114	19	00
Yarra Yarra Creek	BYRO	26	08	10	116	13	20
Yarraloola homestead	YARRALOOLA	21	34	00	115	52	30
Yeelirrie	SIR SAMUEL	27	17		120	05	
Yindagindy Creek (now spelt Indagindi Creek)	WINNING POOL	23	55	10	115	04	10
Yuna	GERALDTON	28	19	30	115	00	00
Z Bend	AJANA	27	39	30	114	27	30
Zuytdorp Cliffs	AJANA/EDEL	27	00		113	49	

Co-ordinates of creeks generally refer to where name is placed on 1:250 000 geological sheet.

TABLE 4. CARNARVON BASIN: IDENTIFIED RECOVERABLE RESERVES AT 31 DECEMBER 1984 (ELLIOTT AND OTHERS, 1985)

	Oil (10^6kL)		*Gas* $C_1 + C_2$ ($10^9 m^3$)		*LPG* $C_3 + C_4$ (10^6kL)		*Condensate* $C_5 + C_6$ (10^6kL)	
	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
PRODUCING FIELDS								
Barrow Island	8.33	8.95	—	10.97	0.05	0.05	—	0.38
North Rankin	—	—	228.70	276.10	15.80	18.20	19.20	22.10
TOTAL	**8.33**	**8.95**	**228.70**	**287.07**	**15.85**	**18.25**	**19.20**	**22.48**
UNDEVELOPED FIELDS								
Angel	—	—	25.80	62.20	—	—	6.10	14.50
Chervil	0.58	0.58	—	—	—	—	—	—
Goodwyn	3.30	6.13	85.00	106.00	8.70	11.10	4.10	20.10
Gorgon	—	—	—	57.19	—	—	—	0.16
Central Gorgon	—	—	—	45.57	—	—	—	0.40
North Gorgon	—	—	—	130.34	—	—	—	1.66
Harriet	1.68	1.68	—	—	—	—	—	—
North Herald	0.23	0.23	—	—	—	—	—	—
Rankin	—	—	5.66	5.66	—	—	0.69	0.69
Scarborough	—	—	170.00	555.00	—	—	—	—
South Pepper	0.90	0.90	—	—	—	—	—	—
Spar	—	—	—	7.04	—	—	—	2.53
Tidepole	0.97	1.18	13.00	17.20	—	—	2.30	3.00
Tubridgi	—	—	2.14	2.16	—	—	—	—
West Tryal Rocks	—	—	—	80.73	—	—	—	3.93
Wilcox	—	—	54.40	91.20	—	—	—	—
TOTAL	**7.66**	**10.70**	**356.00**	**1160.29**	**8.70**	**11.10**	**13.19**	**46.97**
TOTAL RESERVES	**15.99**	**19.65**	**584.70**	**1447.36**	**24.55**	**29.35**	**32.39**	**69.45**

P_1 is the 75% probability and P_2 the 25% probability of recovering a particular volume.

C_1, C_2, C_3, C_4, C_5, and C_6 indicate methane, ethane, propane, butane, pentane, and hexane, respectively.

TABLE 5. WELLS DRILLED FOR PETROLEUM EXPLORATION IN THE CARNARVON BASIN TO THE END OF 1984 (ELLIOTT AND OTHERS, 1985)

Well	*GSWA "S" No*	*Type*	*Location*						*Elevation (m)*				*Total depth (m)*	*Bottomed in*	*Company*	*Year completed*	*Status*
			Lat. (S)			*Long. (E)*											
			D	*M*	*S*	*D*	*M*	*S*									
Airey Hill 1	1629	NFW	23	04	02	113	52	20	GL	68	RT	72	1037	L.Perm	Monarc	1980	W. Well
Airlie 1	369	STR	21	19	30	115	09	55	GL	5	RT	9	2219	U.Juras	WAPET	1967	P & A
Anchor 1	489	NFWO	21	32	51	114	42	37	WD	18	RT	24	3049	L.Juras	WAPET	1969	P & A
Angel 1	664	NFWO	19	30	20	116	35	48	WD	80	DF	9	3411	U.Juras	Wood	1972	G, C, Susp
Angel 2	704	EXTO	19	27	58	116	39	25	WD	86	DF	9	4397	L.Juras	Wood	1972	G, C, Susp
Angel 3	864	EXTO	19	32	30	116	37	43	WD	69	RT	9	3780	U.Juras	Wood	1973	G, C, Susp
Arabella 1	2255	NFWO	20	28	12	116	01	52	WD	42	RT	35	2209	U.Perm	Oxy	1983	P & A
Bambra 1	2266	NFWO	20	31	34	115	37	56	GL	25	RT	32	3666	U.Juras	Oxy	1983	P & A
Bambra 2	2360	NFWO	20	32	44	115	36	02	WD	26	RT	26	4591	M.Juras	Oxy	1983	Susp
Barrow 1 (L-54-J)	153	NFW	20	49	06	115	23	38	GL	52	RT	55	2982	U.Juras	WAPET	1964	O, G
Barrow 2 (L-72)	173	EXT	20	49	40	115	23	07	GL	47	DF	50	2329	U.Juras	WAPET	1964	O, G
Barrow 3 (L-74)	180	EXT	20	49	39	115	23	36	GL	46	RT	49	2210	U.Juras	WAPET	1964	O, G
Barrow 4 (F-36)	184	EXT	20	50	32	115	23	05	GL	31	DF	34	2382	U.Juras	WAPET	1965	O
Barrow 5 (L-16)	189	EXT	20	48	03	115	23	40	GL	66	RT	69	2252	U.Juras	WAPET	1965	G
Barrow 6 (L-56)	200	EXT	20	48	55	115	23	40	GL	62	RT	65	2355	U.Juras	WAPET	1965	O
Barrow 7 (X-62)	212	EXT	20	43	58	115	25	25	GL	46	RT	49	2439	U.Juras	WAPET	1965	O
Barrow 8 (L-58)	224	EXT	20	48	58	115	23	53	GL	64	RT	67	2256	U.Juras	WAPET	1965	O
Barrow 9 (D-14)	231	EXT	20	51	38	115	24	55	GL	14	RT	18	2432	U.Juras	WAPET	1965	O
Barrow 10 (E-14)	239	EXT	20	49	54	115	24	50	GL	36	RT	29	750	L.Cret	WAPET	1965	O
Barrow 11 (F-52)	240	EXT	20	50	43	115	22	30	GL	34	RT	38	695	L.Cret	WAPET	1965	O
Barrow 12 (M-54)	245	EXT	20	48	58	115	24	49	GL	50	RT	53	781	L.Cret	WAPET	1965	O
Barrow 13 (G-16)	248	EXT	20	49	50	115	21	34	GL	38	RT	42	718	L.Cret	WAPET	1965	O
Barrow 14 (L-52)	254	EXT	20	48	58	115	22	30	GL	51	RT	55	724	L.Cret	WAPET	1965	O
Barrow 15 (G-76)	255	EXT	20	51	08	115	21	34	GL	27	RT	30	686	L.Cret	WAPET	1965	O
Barrow 16 (B-12)	256	EXT	20	51	34	115	20	39	GL	20	RT	23	731	L.Cret	WAPET	1965	O
Barrow 17 (K-52)	261	EXT	20	50	43	115	20	39	GL	28	RT	32	948	L.Cret	WAPET	1965	O
Barrow 18 (N-52)	262	EXT	20	48	58	115	26	30	GL	10	RT	21	799	L.Cret	WAPET	1965	O
Barrow 19 (Q-52)	265	EXT	20	47	12	115	22	30	GL	39	RT	42	749	L.Cret	WAPET	1966	O
Barrow 20 (P-74)	266	EXT	20	47	40	115	24	49	GL	33	RT	36	751	L.Cret	WAPET	1966	O
Barrow 21 (H-38)	267	EXT	20	50	17	115	25	11	GL	28	RT	32	742	L.Cret	WAPET	1966	O
Barrow 22 (F-76)	274	EXT	20	51	08	115	23	25	GL	07	RT	11	826	L.Cret	WAPET	1966	O
Barrow 23 (T-74)	279	EXT	20	45	54	115	23	53	GL	58	RT	61	786	L.Cret	WAPET	1966	O
Barrow 24 (L-32-J)	280	EXT	20	48	01	115	22	30	GL	51	RT	55	2240	U.Juras	WAPET	1966	O, G
Barrow 25 (BB-52-J)	297	EXT	20	40	18	115	26	17	GL	16	RT	19	2534	U.Juras	WAPET	1966	P & A
Barrow 26 (X-53)	304	EXT	20	43	38	115	25	35	GL	52	RT	56	2400	U.Juras	WAPET	1966	G, C
Barrow 27 (L-76-J)	306	EXT	20	49	24	115	23	25	GL	66	RT	69	2226	U.Juras	WAPET	1966	G

Barrow 28 (L-45-J)	314	EXT	20	48	45	115	23	12	GL	57	RT	61	2134	U.Juras	WAPET	1966	O
Barrow Deep 1	758	DPT	20	50	07	115	22	56	GL	38	RT	46	4650	M.Juras	WAPET	1973	G, SI
Barrow AA72M	2325	NPW	20	42	35	115	26	22	GL	11	RT	15	1326	L.Cret	WAPET	1983	O, SI
Barrow E11M	2650	EXT	20	49	47	115	24	04	GL	37	RT	41	975	L.Cret	WAPET	1984	O
Barrow E31M	1686	NPW	20	50	22	115	24	10	GL	17	RT	21	945	L.Cret	WAPET	1980	O
Barrow F12M	2310	EXT	20	49	49	115	22	25	GL	36	RT	40	946	L.Cret	WAPET	1983	O
Barrow F16M	2650	EXT	20	49	47	115	23	22	GL	47	RT	50	945	L.Cret	WAPET	1985	O
Barrow F37M	2650	EXT	20	15	14	115	23	37	GL	26	RT	30	926	L.Cret	WAPET	1984	Susp
Barrow F42M3	2310	EXT	20	50	28	115	22	29	GL	34	RT	38	948	L.Cret	WAPET	1983	O
Barrow F45M	2650	EXT	20	50	26	115	23	09	GL	19	RT	23	425	L.Cret	WAPET	1984	O
Barrow F48	1617	NPW	20	50	38	115	23	58	GL	12	RT	16	901	L.Cret	WAPET	1980	SI
Barrow F71M	2650	EXT	20	51	07	115	22	14	GL	19	RT	23	887	L.Cret	WAPET	1984	O
Barrow F72	1546	NPW	20	51	12	115	22	40	GL	12	RT	29	796	L.Cret	WAPET	1979	O
Barrow G27M	2650	EXT	20	50	00	115	21	44	GL	38	RT	42	945	L.Cret	WAPET	1984	O
Barrow G57M	2650	EXT	20	50	40	115	21	46	GL	43	RT	47	974	L.Cret	WAPET	1984	O
Barrow J27M	2650	EXT	20	48	30	115	19	56	GL	19	RT	22	1036	L.Cret	WAPET	1984	Susp
Barrow J46	1664	NPW	20	48	42	115	19	51	GL	14	RT	18	783	L.Cret	WAPET	1980	O
Barrow K46M	1977	SPT	20	48	43	115	21	35	GL	57	RT	60	983	L.Cret	WAPET	1981	O, SI
Barrow K78M	2650	EXT	20	49	23	115	21	60	GL	43	RT	47	948	L.Cret	WAPET	1984	O
Barrow L26M	2650	EXT	20	48	17	115	23	24	GL	62	RT	65	1003	L.Cret	WAPET	1984	SI
Barrow L42M	2310	EXT	20	48	44	115	22	28	GL	50	RT	54	986	L.Cret	WAPET	1983	O
Barrow L45M	1619	NPW	20	48	55	115	23	21	GL	52	RT	56	976	L.Cret	WAPET	1980	O
Barrow L46G	1929	SPT	20	48	48	115	23	28	GL	50	RT	53	585	L.Cret	WAPET	1981	O, SI
Barrow L48M	2650	EXT	20	48	44	115	23	51	GL	38	RT	41	970	L.Cret	WAPET	1984	SI
Barrow L51J	1411	NPW	20	49	05	115	22	22	GL	40	RT	43	2134	U.Juras	WAPET	1978	O
Barrow L54M	2079	SPT	20	48	56	115	22	57	GL	48	RT	52	965	L.Cret	WAPET	1982	O
Barrow L56M	2081	SPT	20	50	40	115	21	31	GL	32	RT	35	1014	L.Cret	WAPET	1982	O
Barrow L58M	2083	SPT	20	49	02	115	23	55	GL	54	RT	57	1030	L.Cret	WAPET	1982	O
Barrow L63M	2310	EXT	20	49	06	115	22	38	GL	45	RT	49	981	L.Cret	WAPET	1983	O
Barrow L76M	1981	SPT	20	49	29	115	23	31	GL	57	RT	61	995	L.Cret	WAPET	1982	O
Barrow M84M	2650	NFWO	20	49	35	115	24	44	GL	38	RT	42	1017	L.Cret	WAPET	1984	SI
Barrow 081	2310	EXT	20	48	00	115	26	08	GL	11	RT	14	810	L.Cret	WAPET	1983	SI
Barrow Q11	2306	EXT	20	46	25	115	22	22	GL	47	RT	50	815	L.Cret	WAPET	1982	O
Barrow Q21	2306	EXT	20	46	39	115	22	23	GL	46	RT	50	852	L.Cret	WAPET	1982	Susp
Barrow Q46M	1688	SPT	20	47	08	115	23	31	GL	58	RT	60	052	L.Cret	WAPET	1980	O
Barrow Q47M	2650	EXT	20	47	09	115	23	44	GL	57	RT	61	075	L.Cret	WAPET	1984	Susp
Barrow R17	2306	EXT	20	46	25	115	21	50	GL	27	RT	30	815	L.Cret	WAPET	1982	Susp
Barrow R18	1904	EXT	20	46	26	115	22	08	GL	48	RT	51	799	L.Cret	WAPET	1981	O
Barrow R27	2306	EXT	20	46	41	115	21	53	GL	20	RT	23	795	L.Cret	WAPET	1982	Susp
Barrow R28	1619	NPW	20	46	37	115	22	07	GL	26	RT	30	789	L.Cret	WAPET	1980	O
Barrow R33M	1906	NPW	20	46	56	115	20	59	GL	18	RT	22	1080	L.Cret	WAPET	1981	O
Barrow R36	1698	EXT	20	46	50	115	21	35	GL	11	RT	15	774	L.Cret	WAPET	1980	O

For key to abbreviations refer to end of Table 5.

TABLE 5. WELLS DRILLED FOR PETROLEUM EXPLORATION IN THE CARNARVON BASIN TO THE END OF 1984 (ELLIOTT AND OTHERS, 1985) (continued).

Well	*GSWA "S" No*	*Type*	*Location*						*Elevation (m)*				*Total depth (m)*	*Bottomed in*	*Company*	*Year completed*	*Status*
			Lat. (S)			*Long. (E)*											
			D	*M*	*S*	*D*	*M*	*S*									
Barrow R38	1596	NPW	20	46	50	115	22	07	GL	23	RT	27	1037	L.Cret	WAPET	1980	O
Barrow R43	1974	EXT	10	47	03	115	20	57	GL	10	KB	14	829	L.Cret	WAPET	1981	Susp
Barrow R63	1919	EXT	20	47	35	115	21	01	GL	40	KB	44	814	L.Cret	WAPET	1981	O
Barrow S53	1410	NPW	20	45	20	115	21	54	GL	8	RT	11	802	L.Cret	WAPET	1978	P & A
Barrow S62M	1902	NPW	20	45	43	115	21	39	GL	9	RT	12	1094	L.Cret	WAPET	1981	SI
Barrow S84	2306	EXT	20	46	08	115	22	11	GL	42	RT	45	825	L.Cret	WAPET	1982	O
Barrow T12	1598	NPW	20	44	43	115	23	33	GL	42	RT	46	1192	L.Cret	WAPET	1980	G, SI
Barrow T24	1684	NPW	20	44	48	115	23	57	GL	41	RT	45	820	L.Cret	WAPET	1980	SI
Barrow U63	2325	NPW	20	45	42	115	25	41	GL	24	RT	27	810	L.Cret	WAPET	1983	O
Barrow X62M	2310	EXT	20	44	01	115	25	19	GL	38	RT	42	1271	L.Cret	WAPET	1983	P & A
Barrow X81M	2325	NPW	20	44	27	115	25	13	GL	48	RT	52	1243	L.Cret	WAPET	1983	O, SI
Barrow X86	2325	NPW	20	44	26	115	26	21	GL	33	RT	36	1276	L.Cret	WAPET	1983	O, SI
Barrow Y23M	2306	EXT	20	43	08	115	23	47	GL	27	RT	31	1288	L.Cret	WAPET	1982	Susp
Barrow Y24	567	SPT	20	43	08	115	23	57	GL	28	RT	32	2293	L.Cret	WAPET	1970	O
Barrow Y24M	1653	NPW	20	43	08	115	23	55	GL	29	RT	33	1249	L.Cret	WAPET	1980	O
Barrow Y25M	2306	EXT	20	43	10	115	24	17	GL	33	RT	37	1274	L.Cret	WAPET	1983	O, Susp
Barrow Y35M	2306	EXT	20	43	18	115	24	11	GL	26	RT	29	1300	L.Cret	WAPET	1983	O, Susp
Barrow Y43M	2310	EXT	20	43	35	115	23	41	GL	30	RT	33	1255	L.Cret	WAPET	1983	SI
Barrow Y44M	2310	EXT	20	43	36	115	23	50	GL	27	RT	30	1260	L.Cret	WAPET	1983	O
Barrow Y53M	2310	EXT	20	43	52	115	23	49	GL	36	RT	40	1250	L.Cret	WAPET	1983	O
Barrow Y54M	2310	EXT	20	43	48	115	23	59	GL	28	RT	31	1245	L.Cret	WAPET	1983	O
Barrow Y63M	2310	EXT	20	44	02	115	23	48	GL	38	RT	42	1225	L.Cret	WAPET	1983	O, SI
Basil 1	2516	NFWO	21	18	37	115	11	36	WD	16	RT	32	2347	M.Juras	Wesmin	1983	P & A
Beagle 1	469	STR	21	11	20	115	38	29	GL	5	RT	6	559	L.Perm	WAPET	1969	P & A
Bidgemia 1	805	STR	25	16	00	115	20	20	GL	89	DF	190	212	L.Perm	Hartog	1972	P & A
Biggada 1	1136	DPT	20	48	36	115	23	10	GL	55	RT	63	3624	M.Juras	WAPET	1975	G, SI
Bluebell 1	2315	NFWO	20	15	30	114	57	04	WD	80	RT	25	4605	U.Trias	WAPET	1983	P & A
BMR 5 (Giralia)	—	STR	22	39	31	114	14	45	GL	74	RT	76	631	L.Perm	BMR	1958	P & A
BMR 6 (Muderong)	—	STR	24	05	55	114	46	20	GL	75	DF	176	305	L.Perm	BMR	1958	P & A
BMR 7 (Muderong)	—	STR	24	05	55	114	46	30	GL	74	DF	176	609	L.Perm	BMR	1958	P & A
BMR 8 (Mt. Madeline)	—	STR	25	44	50	115	38	23	GL	44	DF	245	916	L.Perm	BMR	1959	P & A
BMR 9 (Daurie Ck.)	—	STR	25	33	17	115	53	17	GL	274	DF	276	701	L.Perm	BMR	1959	P & A
Bounty 1	2338	NFWO	19	17	22	116	38	22	WD	146	RT	08	3524	U.Juras	MPA	1983	P & A
Bowers 1	2114	NFWO	21	06	14	114	42	54	WD	133	RT	25	4300	U.Trias	WAPET	1982	P & A
Brigadier 1	1426	NFWO	19	05	49	116	08	09	WD	313	RT	8	4292	U.Trias	Wood	1978	P & A
Bundegi 1	1315	NFWO	22	01	06	114	09	33	WD	16	RT	31	3096	M.Trias	WAPET	1978	P & A
Burna 1	2629	NFW	23	39	58	114	26	24	GL	81	RT	96	768	U.Carb	Esso	1984	P & A
Campbell 1	1452	NFWO	20	24	42	115	43	00	WD	141	RT	22	2750	U.Juras	WAPET	1979	P & A
Candace 1	2202	NFWO	20	49	37	115	55	07	WD	21	RT	32	2063	L.Perm	Oxy	1982	P & A
Cane River 1	670	STR	21	40	51	115	05	54	GL	8	KB	10	694	L.Carb	Hemat	1971	P & A
Cane River 2	688	STR	21	38	13	115	15	51	GL	5	KB	7	413	L.Cret	Hemat	1971	P & A
Cane River 3	689	STR	21	42	28	115	19	28	GL	15	KB	17	255	Precamb	Hemat	1972	P & A

Cane River 4	691	STR	21	35	54	115	33	45	GL	13	KB	16	173	Precamb	Hemat	1972	P & A
Cane River 5	692	STR	21	47	22	115	28	48	GL	34	KB	37	201	Precamb	Hemat	1972	P & A
Cape Cuvier 1	51	STR	24	13	35	113	23	50	GL	72	RT	72	457	M.-U.Dev	WAPET	1955	P & A
Cape Range 1	51	NFW	22	03	57	114	00	38	GL	147	DF	150	2444	M.Juras	WAPET	1954	P & A
Cape Range 2	51	NFW	22	05	57	113	59	32	GL	282	DF	285	4624	L.Juras	WAPET	1956	P & A
Cape Range 3A	51	NFW	22	08	41	113	59	57	GL	267	DF	269	1139	U. Juras	WAPET	1956	P & A
Cape Range 4	51	NFW	22	19	32	113	56	16	GL	131	RT	134	1176	U.Juras	WAPET	1956	P & A
Carnie 1	1997	NFW	21	24	30	115	41	05	GL	7	RT	9	163	L.Cret	Avon	1982	G, Susp
Central Gorgon 1	2363	NFWO	20	28	09	114	48	33	WD	259	RT	25	4598	U.Trias	WAPET	1983	P & A
Chargoo 1	389	NFW	23	35	52	113	55	59	GL	26	RT	28	428	L.Perm	WAPET	1967	P & A
Chervil 1	2333	NFWO	21	18	13	115	13	32	WD	15	RT	43	2661	U. Trias	Mesa	1983	P & A,
Coonga 1	767	STR	21	03	08	116	01	48	GL	6	KB	8	176	Precamb	Hemat	1972	P & A
Cunaloo 1	693	STR	22	00	48	114	53	47	GL	12	RT	15	797	U.Perm	WAPET	1972	P & A
Dailey 1	2553	ESSO	21	38	24	114	33	26	WD	16	RT	35	2541	U.Trias	Esso	1984	P & A
Dampier 1	450	NFWO	19	52	21	116	00	49	WD	76	RT	9	4142	U.Juras	Wood	1969	P & A
De Grey 1	663	NFWO	19	29	20	117	05	08	WD	94	RT	28	2088	Trias	Wood	1971	P & A
Delambre 1	1638	NFWO	18	31	05	116	41	48	WD	884	RT	10	5495	L.Trias	Wood	1980	P & A
Direction Island 1	424	STR	21	32	03	115	07	42	GL	5	RT	6	673	L.Perm	WAPET	1968	P & A
Dirk Hartog 1 to 16	557	STR	25	42	00	112	58	20	GL	1	—	—	237	Eocene	WAPET	1955	P & A
Dirk Hartog 1 to 16				to		113	09	20	to	58	—	—	to 457	Eocene	WAPET	to 1956	
			25	57	45												
Dirk Hartog 17B	557	NFW	25	51	58	113	04	40	GL	87	DF	90	1523	L.Sil	WAPET	1957	P & A
Dixon 1	2540	NFWO	19	51	00	115	47	11	WD	83	RT	17	4357	U.Trias	Wood	1984	P, Susp
Dockrell 1	900	NFWO	19	47	17	115	46	47	WD	110	RT	30	3895	U.Trias	Wood	1973	G, O, Susp
Dorrigo 1	2238	NFWO	20	39	50	115	42	43	WD	27	RT	35	2741	U.Trias	Oxy	1982	P & A
Eaglehawk 1	791	NFWO	19	30	30	116	16	37	WD	120	RT	12	3490	U.Trias	Wood	1972	O, Susp
East Marilla 1	710	STR	22	54	48	114	36	58	GL	59	DF	62	638	L.Carb	WAPET	1972	P & A
East Pepper 1	2587	NFWO	21	06	40	115	19	28	WD	8	RT	28	1320	L.Cret	Wesmin	1984	P & A
Echo Bluff 1	2605	NFW	21	23	26	115	43	29	GL	11	RT	17	1204	M.-U.Dev	Avon	1984	P, Susp
Edel 1	727	NFWO	27	06	48	113	23	24	WD	94	RT	29	2749	?Trias	Ocean	1972	P & A
Eendracht 1	1603	NFWO	19	54	29	112	14	35	WD	1353	RT	10	3410	U.Trias	Esso	1980	P & A
Egret 1	818	NFWO	19	30	23	116	20	50	WD	118	DF	12	3658	U.Trias	Wood	1973	O, Susp
Emma 1	2329	NFWO	20	31	06	115	46	42	WD	37	RT	38	2352	M.Juras	Oxy	1983	P & A
Enderby 1	597	NFWO	20	09	26	116	24	24	WD	54	RT	9	2149	U.Perm	Wood	1970	P & A
Exmouth 1	51	STR	22	23	06	114	06	45	GL	12	DF	15	536	U.Cret	WAPET	1956	W. Well
Exmouth 2	51	STR	22	21	30	114	08	24	GL	18	DF	21	618	U.Cret	WAPET	1956	P & A
Finucane 1	1427	NFWO	19	17	24	116	45	54	WD	139	RT	8	3300	M.Juras	Wood	1978	P & A
Fisher 1	1790	NFWO	19	49	26	115	42	33	WD	88	DF	8	3762	U.Trias	Wood	1981	P & A
Flacourt 1 (Barrow S27)	427	EXT	20	44	54	115	22	50	GL	50	KB	53	817	L.Cret	WAPET	1968	P & A
Flag 1	481	NFWO	20	27	55	115	38	44	WD	37	RT	23	3803	U.Juras	WAPET	1970	P & A
Flinders Shoal 1	472	NFWO	21	04	16	115	31	18	WD	15	RT	26	3616	M.Trias	WAPET	1969	P & A
Flores 1	2434	NFWO	20	45	32	115	35	38	WD	9	RT	31	2119	U.Juras	Oxy	1983	P & A
Fortescue 1	467	STR	21	01	05	115	51	17	GL	5	RT	6	610	L.Perm	WAPET	1969	P & A

For key to abbreviations refer to end of Table 5.

TABLE 5. WELLS DRILLED FOR PETROLEUM EXPLORATION IN THE CARNARVON BASIN TO THE END OF 1984 (ELLIOTT AND OTHERS, 1985) (continued).

Well	GSWA "S" No	Type	Location						Elevation (m)				Total depth (m)	Bottomed in	Company	Year completed	Status
			Lat. (S)			Long. (E)											
			D	M	S	D	M	S									
Gandara 1	1507	NFWO	19	16	31	115	49	15	WD	305	RT	21	4361	U.Trias	Hudbay	1979	P & A
Garden Mill 1	2367	STR	22	33	39	114	28	20	GL	10	RT	12	555	L.Cret	GWHYD	1983	W.Well
Gascoyne 1	2631	NFW	25	02	20	115	01	09	GL	127	RT	128	526	U.Carb	Esso	1984	P & A
Georgette 1	2472	NFWO	20	45	43	115	39	16	WD	20	RT	25	2392	M.Juras	Oxy	1983	P & A
Giralia 1	51	NFW	22	59	38	114	10	06	GL	110	DF	112	1244	L.Perm	WAPET	1955	W. Well
Glenroy 1	328	NFW	21	49	10	114	52	35	GL	3	RT	5	648	L.Cret	WAPET	1966	P & A
Gnaraloo 1	390	NFW	23	40	32	113	40	52	GL	46	RT	48	502	L.Carb	WAPET	1967	P & A
Goodwyn 1	667	NFWO	19	41	37	115	53	44	WD	126	RT	29	3536	M.Trias	Wood	1971	G, C, Susp
Goodwyn 2	709	EXTO	19	39	53	115	51	53	WD	134	DF	13	3750	U.Trias	Wood	1972	G, C, Susp
Goodwyn 3	813	EXTO	19	44	09	115	52	40	WD	121	DF	30	3658	U.Trias	Wood	1973	G, O, Susp
Goodwyn 4	837	EXTO	19	41	38	115	50	54	WD	130	RT	30	3632	U.Trias	Wood	1973	G, O, Susp
Goodwyn 5	1460	EXTO	19	40	42	115	53	45	WD	129	RT	8	3664	U.Trias	Wood	1979	Susp
Goodwyn 6	1917	EXTO	19	43	24	115	51	12	WD	124	RT	8	4664	U.Trias	Wood	1982	Susp, O
Goodwyn 7	2868	EXT	19	36	42	115	57	37	WD	133	RT	17	3446	U.Trias	Wood	1985	G/C Susp
Gorgon 1	1449	NFWO	20	34	43	114	46	22	WD	259	RT	21	4401	U.Trias	WAPET	1981	Susp
Grierson 1	51	STR	24	12	05	113	46	26	GL	12	DF	12	438	M.-U.Dev	WAPET	1955	W. Well
Grierson 2	51	STR	24	12	07	113	47	12	GL	4	DF	4	458	M.-U.Dev	WAPET	1955	P & A
Grierson 3	51	STR	24	12	07	113	45	36	GL	2	DF	2	442	M.-U.Dev	WAPET	1955	P & A
Hampton 1	988	NFWO	20	07	04	116	32	47	WD	53	RT	30	2584	L.Trias	Wood	1974	P & A
Harriet 1	2501	NFWO	20	36	13	115	36	46	WD	23	RT	35	2711	U.Juras	Oxy	1983	G, O, Susp
Harriet 2	2521	EXTO	20	36	16	115	36	45	WD	24	RT	38	2757	L.Cret	Oxy	1984	P & A
Harriet 3	2538	EXTO	20	36	12	115	36	47	WD	23	RT	36	2647	L.Cret	Oxy	1984	Susp, O
Harriet 4	2611	EXTO	20	36	13	115	36	46	WD	23	RT	27	2441	L.Cret	Oxy	1984	Susp, O
Harriet 5	2636	EXTO	20	36	16	115	36	45	WD	24	RT	26	2445	L.Cret	Oxy	1984	Susp, O
Harriet 6	2652	EXTO	20	36	12	115	36	46	WD	23	RT	26	2242	L.Cret	Oxy	1984	Susp, O
Hauy 1	795	NFWO	19	47	39	117	15	15	WD	65	DF	30	825	Precamb	Wood	1972	P & A
Haycock 1	1322	NFWO	19	50	58	115	43	17	WD	85	RT	8	3668	U.Trias	Wood	1977	P & A
Hermite 1	1311	NFWO	20	49	58	115	42	08	WD	16	RT	27	3300	U.Trias	WAPET	1977	P & A
Hilda 1	954	NFWO	21	12	01	114	38	12	WD	145	RT	12	1546	U.Trias	WAPET	1974	P & A
Hilda 1A	954	NFWO	21	11	59	114	38	13	WD	145	RT	12	3466	U.Trias	WAPET	1974	P & A
Hope Island 1	412	STR	22	09	34	114	28	35	GL	5	RT	9	1426	U.Perm	WAPET	1968	P & A
Investigator 1	1478	NFWO	20	21	07	112	58	01	WD	841	RT	10	3746	U.Trias	Esso	1979	P & A
Judy 1	2439	NFWO	20	41	17	115	46	18	WD	26	RT	38	2021	M.Juras	Oxy	1983	P & A
Jupiter 1	1518	NFWO	19	34	53	113	31	58	WD	960	RT	10	4946	U.Trias	Phllps	1979	P & A
Jurabi 1	2100	NFWO	21	36	12	114	11	56	WD	60	RT	17	3712	U.Trias	Esso	1982	P & A
Kalbarri 1	832	STR	27	16	00	114	06	26	GL	129	RT	133	1539	Silur	OPPL	1973	P & A
Kennedy Range 1	322	NFW	24	29	50	114	59	19	GL	295	RT	299	2227	L.Perm	WAPET	1967	P & A
Koolinda 1	1314	NFWO	21	23	46	115	03	13	WD	18	RT	31	3732	M.Juras	WAPET	1978	P & A
Lambert 1	943	NFWO	19	27	23	116	29	23	WD	125	RT	10	3700	L.Juras	Wood	1974	G, O, Sus
Lawley 1	1865	NFWO	19	54	21	117	00	32	WD	60	RT	10	1120	Precamb	Hudbay	1981	P & A
Learmonth 1	51	NFW	22	11	04	114	03	38	GL	20	RT	23	2327	L.Perm	WAPET	1958	P & A
Learmonth 2	136	NFW	22	17	40	114	03	55	GL	22	RT	25	1871	U.Trias	WAPET	1964	P & A

Legendre 1	417	NFWO	19	40	19	116	43	55	WD	52	RT	9	3473	M.Juras	Wood	1968	O, Susp
Legendre 2	600	NFWO	19	36	27	116	46	49	WD	48	RT	9	3618	L.Juras	Wood	1970	P & A
Lenita 1	2665	NFWO	20	34	35	115	38	11	WD	27	RT	27	2232	L.Cret	Oxy	1984	Susp, O
Lenita 2	2830	EXT	20	34	36	115	38	10	WD	24	KB	25	2355	L.Cret	Bond	1985	O, Susp
Lenita 3	2844	EXT	20	34	35	115	38	11	WD	24	KB	25	2181	L.Cret	Bond	1985	O, Susp
Lewis 1	1163	NFWO	19	47	36	116	36	04	WD	60	RT	30	265	—	Wood	1975	P & A
Lewis 1A	1163	NFWO	19	47	36	116	36	04	WD	60	RT	30	3400	L.Juras	Wood	1976	P & A
Locker 1	362	STR	21	43	16	114	45	35	GL	3	RT	4	766	U. Trias	WAPET	1967	P & A
Long Island 1	312	STR	21	37	10	114	41	10	GL	5	RT	9	2158	M.Trias	WAPET	1966	P & A
Lowendal 1	957	NFWO	19	52	48	115	38	02	WD	85	RT	30	3642	U. Trias	Wood	1974	P & A
Madeleine 1	473	NFWO	19	38	59	116	21	30	WD	69	RT	9	4427	U. Juras	Wood	1969	P & A
Malus 1	774	NFWO	19	45	16	115	32	02	WD	86	DF	9	3658	U. Trias	Wood	1972	P & A
Mangrove 1	428	STR	21	14	22	115	46	04	GL	5	RT	6	286	L.Perm	WAPET	1968	P & A
Mardie 1	349	STR	21	21	14	115	42	23	GL	5	RT	6	222	Perm	WAPET	1967	Susp
Mardie 1A	1079	STR	21	21	18	115	41	43	GL	5	RT	8	164	L.Cret	WAPET	1974	Susp
Mardie 2	474	STR	21	20	42	115	43	28	GL	6	RT	8	165	L.Cret	WAPET	1969	Susp
Mardie West 1	763	STR	21	11	56	115	55	24	GL	6	RT	9	135	Precamb	Hemat	1972	P & A
Marilla 1	70	STR	22	55	45	114	30	00	GL	47	KB	49	457	U.Sil	WAPET	1963	P & A
Mary Anne 1	421	STR	21	17	55	115	30	04	GL	5	RT	6	533	M.Trias	WAPET	1968	P & A
Mercury 1	1544	NFWO	19	33	55	113	52	42	WD	1142	RT	10	3812	U.Trias	Phllps	1979	P & A
Merlinleigh 1	300	STR	24	29	53	114	59	21	GL	290	RT	292	305	L.Perm	WAPET	1966	P & A
Merlinleigh 2	300	STR	24	28	50	114	59	33	GL	293	RT	294	306	L.Perm	WAPET	1966	P & A
Merlinleigh 3	300	STR	24	29	13	115	00	00	GL	294	RT	295	166	L.Perm	WAPET	1966	P & A
Merlinleigh 4	300	STR	24	29	13	114	59	03	GL	290	RT	291	136	L.Perm	WAPET	1966	P & A
Merlinleigh 5	300	STR	24	28	32	114	59	13	GL	290	RT	292	175	L.Perm	WAPET	1966	P & A
Mermaid 1	1313	NFWO	20	41	55	115	57	35	WD	25	RT	56	1271	Precamb	WAPET	1978	P & A
Middle Island 1	2181	NFWO	20	55	07	115	19	49	WD	5	RT	10	2408	U.Juras	WAPET	1982	P & A
Miller 1	1397	NFWO	19	34	45	116	09	55	WD	131	RT	8	3520	U.Trias	Wood	1978	P & A
Minderoo 1	70	STR	21	50	40	115	04	40	GL	11	KB	12	610	U.Carb	WAPET	1963	P & A
Montague 1	2583	NFWO	19	31	41	116	21	04	WD	115	RT	17	4362	U.Trias	Esso	1985	P & A
Moogooree 1	781	STR	24	15	20	115	15	30	GL	253	DF	254	128	L.Perm	Hartog	1972	P & A
Moogooree 2	793	STR	24	16	50	115	12	40	GL	257	DF	258	192	L.Perm	Hartog	1972	P & A
Muiron 1	397	STR	21	39	04	114	21	18	GL	5	RT	9	1785	Juras	WAPET	1967	P & A
Multhawarra 1	2207	NFW	21	19	35	115	42	15	GL	3	RT	5	185	L.Cret	Avon	1982	P & A
Mulyery 1	404	STR	21	18	26	115	47	48	GL	5	RT	6	140	L.Cret	WAPET	1968	P & A
Murat 1	2040	NFW	21	52	23	114	08	42	GL	4	RT	9	2410	L.Juras	Mesa	1982	P & A
Murnda 1	2348	STR	21	21	14	115	41	20	GL	5	RT	7	252	U.Dev	Avon	1983	Susp
Myanore 1	2350	NFW	21	20	39	115	41	40	GL	5	RT	7	175	U.Dev	Avon	1983	P & A
Nelson Rocks 1	899	NFWO	19	33	37	116	51	13	WD	75	RT	10	2190	U.Juras	Wood	1973	P & A
Ningaloo 1	632	NFW	22	34	25	113	46	40	GL	140	RT	108	1228	M.-U.Juras	WAPET	1971	P & A
North Gorgon 1	1891	NFWO	20	23	04	114	51	42	WD	215	RT	25	4500	U.Trias	WAPET	1983	P & A
North Herald 1	2335	NFWO	21	10	34	115	16	02	WD	19	RT	27	2600	L.Juras	Mesa	1983	P & A, Re-ent
North Herald 2	2877	Ext	21	10	37	115	16	34	WD	16	RT	31	1300	L.Cret	Wesmin	1985	O, Susp
North Rankin 1	640	NFWO	19	35	55	116	07	30	WD	122	RT	30	3534	U.Trias	Wood	1971	G, C, Susp
North Rankin 2	729	EXTO	19	33	54	116	08	46	WD	126	RT	12	3750	U.Trias	Wood	1972	G, C, Susp
North Rankin 3	757	EXTO	19	31	49	116	10	21	WD	125	RT	30	4093	U.Trias	Wood	1972	G, C, Susp
North Rankin 4	772	EXTO	19	35	07	116	06	42	WD	127	RT	30	4062	L.Juras	Wood	1972	G, C, Susp
North Rankin 5	584	EXTO	19	34	19	116	09	30	WD	123	RT	30	3500	U.Trias	Wood	1977	G, Susp

For key to abbreviations refer to end of Table 5.

TABLE 5. WELLS DRILLED FOR PETROLEUM EXPLORATION IN THE CARNARVON BASIN TO THE END OF 1984 (ELLIOTT AND OTHERS, 1985) (continued).

Well	GSWA "S" No	Type	Location						Elevation (m)				Total depth (m)	Bottomed in	Company	Year completed	Status
			Lat. (S)			Long. (E)											
			D	M	S	D	M	S									
North Rankin 6	1674	EXTO	19	32	46	116	08	27	WD	124	RT	8	3900	U.Trias	Wood	1981	Susp
North Sandy 1	422	STR	21	06	25	115	38	56	GL	5	RT	6	610	M.Trias	WAPET	1968	P & A
North Tryal Rocks 1	720	NFWO	19	59	18	115	19	11	WD	107	DF	12	3658	U.Trias	WAPET	1972	P & A
Novara 1	2144	NFWO	21	21	26	114	04	30	WD	372	RT	8	2753	L.Cret	Esso	1982	P & A
Observation 1	407	STR	21	44	28	114	32	12	GL	5	RT	9	2289	M.Trias	WAPET	1968	P & A
Onslow 1	313	NFW	21	45	56	114	52	17	GL	0	RT	5	2998	L.Perm	WAPET	1966	P & A
Outtrim 1	2533	NFWO	21	31	53	114	27	03	WD	91	RT	30	1725	U.Juras	Esso	1984	P & A
Parker 1	1541	NFWO	20	00	08	115	40	08	WD	80	RT	8	4737	L.Juras	Wood	1980	P & A
Pasco 1	346	NFW	20	58	20	115	19	30	GL	8	RT	12	1899	L.Cret	WAPET	1967	O, G, SI
Pasco 2	370	EXT	20	57	41	115	19	20	GL	4	RT	8	2441	L.Cret	WAPET	1967	P & A
Pasco 3	382	EXT	20	58	09	115	19	52	GL	1	RT	15	2451	L.Cret	WAPET	1967	O, SI
Pasco 4	2244	EXT	20	58	23	115	19	32	GL	7	RT	10	2170	L.Cret	WAPET	1983	P & A
Paterson 1	113	NFW	22	27	34	113	55	56	GL	98	DF	101	2286	U.Juras	WAPET	1964	P & A
Peak 1	387	STR	21	36	17	114	30	22	GL	5	RT	9	2141	U.Juras	WAPET	1967	P & A
Peedamullah 1	403	STR	21	24	26	115	37	50	GL	5	RT	7	328	L.Cret	WAPET	1968	P & A
Pendock 1	493	NFWO	23	16	52	113	20	10	WD	133	RT	10	2501	U.Silur	CSO	1969	P & A
Pepper 1	550	NFWO	21	03	28	115	18	04	WD	8	RT	27	2743	M.Juras	WAPET	1970	P & A
Perentie 1	1125	NFW	20	53	02	115	23	41	GL	7	RT	15	3900	M.Juras	WAPET	1976	G, SI
Pueblo 1	746	NFWO	19	46	02	115	51	44	WD	112	RT	30	3485	U.Trias	Wood	1979	P & A
Quail 1	67	NFW	23	57	04	114	29	57	GL	115	DF	118	3580	Sil	WAPET	1964	P & A
Quobba 1	2542	NFW	24	20	45	113	26	09	GL	53	RT	56	1931	Sil	CNW	1984	Abd, W. Well
Rankin 1	654	NFWO	19	47	56	115	44	31	WD	93	RT	9	4110	M-U. Trias	Wood	1971	G,C,O, Susp
Remarkable Hill 1	443	NFW	22	57	20	114	09	20	GL	107	KB	111	3206	U.Carb	MPA	1969	P & A
Resolution 1	1535	NFWO	21	17	56	113	41	24	WD	1086	RT	10	3884	U.Trias	Esso	1979	P & A
Ripple Shoals1	518	NFWO	21	07	10	115	24	06	WD	8	RT	24	2279	M.-U.Juras	WAPET	1970	P & A
Rosemary 1	796	NFWO	19	57	16	116	20	41	WD	65	DF	9	3909	L.Juras	Wood	1973	P & A
Rosemary North 1	2248	NFWO	19	54	43	116	24	38	WD	65	RT	17	2263	U.Juras	Wood	1982	P & A
Rosily 1	2031	NFWO	21	12	08	114	52	01	WD	125	RT	25	218	Tert	WAPET	1982	P & A
Rosily 1A	2031	NFWO	21	12	10	114	52	00	WD	95	RT	25	3066	U.Cret	WAPET	1982	P & A
Rough Range 1	51	NFW	22	25	12	114	05	00	GL	57	RT	61	4452	Dev	WAPET	1955	O, P & A
Rough Range 1A	51	EXT	22	25	11	114	05	02	GL	57	RT	60	1115	L.Cret	WAPET	1955	O, SI
Rough Range 2	51	EXT	22	25	55	114	04	12	GL	95	RT	98	1243	U.Juras	WAPET	1954	P & A
Rough Range 3	51	EXT	22	24	45	114	05	16	GL	61	RT	64	1193	L.Cret	WAPET	1954	P & A
Rough Range 4	51	EXT	22	25	28	114	05	00	GL	60	RT	62	1146	L.Cret	WAPET	1954	P & A
Rough Range 5	51	EXT	22	25	12	114	04	40	GL	72	RT	74	1150	L.Cret	WAPET	1954	P & A
Rough Range 6	51	EXT	22	25	18	114	04	55	GL	61	RT	63	1127	L.Cret	WAPET	1955	P & A
Rough Range 7	51	EXT	22	26	45	114	04	13	GL	86	RT	88	1305	L.Cret	WAPET	1955	P & A
Rough Range 8	51	EXT	22	26	51	114	03	51	GL	102	RT	105	1195	L.Cret	WAPET	1955	P & A
Rough Range 9	51	EXT	22	26	55	114	04	29	GL	51	RT	54	1172	L.Cret	WAPET	1955	P & A
Rough Range 10	51	EXT	22	25	06	114	05	02	GL	64	RT	66	1140	L.Cret	WAPET	1957	P & A
Rough Range South 1	51	STR	22	37	21	113	57	43	GL	85	RT	88	874	L.Cret	WAPET	1956	P & A
Rough Range South 2	51	STR	22	33	52	114	00	18	GL	79	RT	82	464	L.Tert	WAPET	1956	P & A

Rough Range South 3	51	STR	22	30	14	114	02	36	GL	56	RT	59	579	U.Cret	WAPET	1956	P & A
Rough Range South 4	51	STR	22	32	05	114	01	35	GL	67	RT	70	698	U.Cret	WAPET	1956	P & A
Rough Range South 5	51	NFW	22	34	30	113	59	22	GL	106	RT	109	1451	L.Perm	WAPET	1956	P & A
Rough Range South 6	51	STR	22	32	27	114	00	49	GL	97	RT	99	486	U.Cret	WAPET	1956	P & A
Sable 1	752	NFWO	19	14	04	116	54	59	WD	151	DF	12	3972	U.Trias	Wood	1972	P & A
Saddleback 1	1993	NFW	21	26	30	115	46	30	GL	22	RT	24	148	L.Cret	Avon	1982	P & A
Sampson 1	2659	NFWO	19	43	39	116	38	39	WD	57	RT	17	3750	M.Juras	Wood	1984	P & A
Sandy Point 1	402	NFW	22	25	49	113	47	49	GL	112	RT	115	3045	L.Juras	WAPET	1968	P & A
Sandy Point 2	630	NFW	22	22	16	113	50	41	GL	99	RT	103	1680	U.Juras	WAPET	1971	P & A
Saturn 1	1588	NFWO	19	54	36	114	56	41	WD	1178	RT	11	4000	U.Trias	Phllps	1981	P & A
Scarborough 1	1553	NFWO	19	53	07	113	08	45	WD	923	RT	10	2360	L.Cret	Esso	1979	G, Susp
Serrurier 1	2283	NFWO	21	34	39	114	42	09	WD	8	RT	25	1625	U.Juras	Esso	1983	P & A
Sholl Island 1	296	STR	20	57	00	115	53	50	GL	5	RT	9	1272	L.Perm	WAPET	1967	P & A
Sirius 1	1691	NFWO	20	53	04	112	41	21	WD	1174	RT	10	3500	U.Trias	Esso	1980	P & A
South Chervil 1	2507	NFWO	21	20	40	115	12	12	WD	16	RT	30	2282	U.Juras	Wesmin	1983	P & A, Re-ent
South Pepper 1	2250	NFWO	21	07	30	115	16	29	WD	17	RT	32	2550	L.Cret	Mesa	1983	G, O, Susp
South Pepper 2	2490	NFWO	21	08	32	115	16	30	WD	19	RT	30	1300	U.Juras	Mesa	1983	P & A
South Pepper 3	2505	EXTO	21	07	21	115	15	01	WD	18	RT	31	2290	L.Cret	Wesmin	1984	P & A
South Pepper 4	2545	EXTO	21	07	35	115	17	14	WD	17	RT	32	1300	L.Cret	Wesmin	1984	P, Susp
Spar 1	1248	NFWO	20	36	52	114	53	06	WD	114	RT	30	3721	L. Cret	WAPET	1976	P & A
Stokes Point 1	423	NFW	20	52	55	115	22	55	GL	17	RT	22	2484	U.Juras	WAPET	1968	O, SI
Strickland 1	2097	NFWO	20	12	31	116	41	02	WD	47	RT	9	1050	M.Trias	Hudbay	1982	P & A
Sultan 1	1447	NFWO	20	02	38	115	11	21	WD	146	RT	21	3620	U.Trias	WAPET	1979	P & A
Surprise 1	764	STR	21	17	58	115	49	27	GL	10	KB	12	216	U. Carb	Hemat	1972	P & A
Talisman 1	2589	NFWO	19	29	43	116	56	24	WD	78	RT	18	2925	M.Juras	Marath	1984	Susp, O
Talisman 2	2788	EXT	19	30	21	116	55	35	WD	78	KB	25	2326	U.Juras	MPA	1985	P & A
Tamala 1	833	STR	26	38	48	113	38	04	GL	3	KB	7	1225	Sil	OPPL	1973	P & A
Thevenard 1	418	NFW	21	27	45	115	01	05	GL	5	RT	9	2076	U.Juras	WAPET	1968	P & A
Thringa 1	1995	NFW	21	21	15	115	41	00	GL	6	RT	8	173	L. Cret	Avon	1982	G, Susp
Tidepole 1	1149	NFWO	19	46	07	115	53	06	WD	110	RT	30	3491	U.Trias	Wood	1975	G, C, O, Susp
Tortoise Island 1	327	STR	21	35	13	114	51	18	GL	5	RT	9	2134	U.Juras	WAPET	1966	P & A
Trimouille 1	343	STR	20	24	11	115	34	09	GL	5	RT	9	2435	L.Cret	WAPET	1967	P & A
Trimouille 1A	345	STR	20	24	11	115	34	09	GL	5	RT	9	686	L. Tert	WAPET	1967	P & A
Trimouille 1B	368	STR	20	24	18	115	34	16	GL	4	RT	5	229	U. Tert	WAPET	1967	P & A
Tryal Rocks 1	560	NFWO	20	24	48	115	09	10	WD	46	RT	28	3695	U.Juras	WAPET	1970	P & A
Tubridgi 1	1840	NFW	21	48	30	114	48	55	GL	4	RT	7	611	M-U. Trias	Otter	1981	Susp, Prod.
Tubridgi 2	1921	EXT	21	46	55	114	50	45	GL	0	RT	2	592	M-U.Trias	Otter	1981	Susp, Prod.
Tubridgi 3	1923	EXT	21	47	26	114	48	18	GL	5	KB	4	597	U. Trias	Otter	1981	P & A
Tubridgi 4	1925	EXT	21	45	52	114	49	58	GL	0	KB	3	595	U. Trias	Otter	1981	Susp, Prod.
Tubridgi 5	1952	EXT	21	45	23	114	51	07	GL	0	KB	3	593	U.Trias	Otter	1981	Susp, Prod.
Tubridgi 6	2012	EXT	21	44	41	114	52	26	GL	0	RT	3	593	U.Trias	Otter	1982	G
Urala 1	438	STR	21	49	06	114	43	22	GL	2	RT	4	762	U. Trias	WAPET	1968	P & A
Vinck 1	1581	NFWO	20	35	04	112	11	34	WD	1373	RT	10	4600	U.Trias	Esso	1980	P & A
Vlaming Head 1	2035	NFWO	21	14	48	114	11	26	WD	336	RT	25	2068	L.Cret	CNW	1982	P & A
Walcott 1	1533	NFWO	19	37	05	116	22	17	WD	81	RT	8	4383	M.Trias	Wood	1979	P & A
Wandagee 1	19	STR	23	53	15	114	23	51	GL	69	DF	72	1073	Sil	WAPET	1962	W. Well
Warroora 1	51	NFW	23	30	35	113	52	55	GL	26	DF	29	1826	?Carb	WAPET	1955	W. Well

For key to abbreviations refer to end of Table 5.

TABLE 5. WELLS DRILLED FOR PETROLEUM EXPLORATION IN THE CARNARVON BASIN TO THE END OF 1984 (ELLIOTT AND OTHERS, 1985) (continued).

Well	*GSWA "S" No*	*Type*	*Location*						*Elevation (m)*				*Total depth (m)*	*Bottomed in*	*Company*	*Year completed*	*Status*
			Lat. (S)			*Long. (E)*											
			D	*M*	*S*	*D*	*M*	*S*									
Weelawarren 1	2357	NFW	21	48	43	114	55	14	GL	6	RT	8	553	M.Trias	Pancon	1983	P & A
West Barrow 1	2053	NFWO	20	53	26	114	54	53	WD	98	RT	10	494	Tert	OFFO	1982	Abd
West Barrow 1A	2053	NFWO	20	53	27	115	54	53	WD	98	RT	10	3520	L.Cret	OFFO	1982	Susp
West Muiron 1	751	NFWO	23	33	56	114	14	41	WD	142	DF	12	781	U. Cret	WAPET	1972	P & A
West Muiron 1A	751	NFWO	21	34	14	114	14	45	WD	62	DF	12	345	Tert	WAPET	1972	P & A
West Muiron 2	955	NFWO	21	35	39	114	13	31	WD	62	RT	30	3320	U.Trias	WAPET	1975	P & A
West Tryal Rocks 1	778	NFWO	20	13	45	115	02	04	WD	138	RT	12	3866	L.Trias	WAPET	1973	G, C, P & A
West Tryal Rocks 2	1075	EXTO	20	12	56	115	03	56	WD	126	RT	12	3825	L.Trias	WAPET	1974	G, C, P & A
West Tryal Rocks 3	1894	EXTO	20	09	18	115	02	57	WD	165	RT	25	4035	U.Trias	WAPET	1982	P & A
Whaleback 1	68	NFW	22	43	35	113	51	37	GL	54	DF	57	1528	L.Perm	WAPET	1963	P & A
Whitlock 1	1249	NFW	20	43	45	115	24	55	GL	41	RT	49	2400	U.Juras	WAPET	1976	P & A
Wilcox 1	2269	NFWO	20	00	32	115	29	01	WD	72	RT	17	4024	U.Trias	Wood	1983	G, C, P & A
Wilcox 2	2733	EXT	19	59	24	115	30	18	WD	73	RT	17	2448	U. Trias	Wood	1985	P & A
Windoo 1	765	STR	21	21	18	115	40	55	GL	2	KB	4	219	L. Cret	Hemat	1972	P & A
Windoo 1A	1078	STR	21	21	18	115	40	55	GL	2	RT	5	174	L. Cret	WAPET	1974	Susp
Withnell 1	745	NFWO	20	01	11	115	48	15	WD	75	RT	30	4650	M.Juras	Wood	1976	P & A
Wonangarra 1	463	STR	22	09	03	114	41	20	GL	6	RT	8	575	L.Carb	WAPET	1969	P & A
Woodleigh 1981/2	2075	STR	26	03	22	114	40	02	GL	110	RT	110	189	Precamb	Elvet	1981	P & A
Woorawa 1	766	STR	21	21	55	115	47	33	GL	13	KB	16	202	U.Carb	Hemat	1972	P & A
Wyloo 1	1859	NFW	21	47	36	114	48	16	GL	2	KB	5	732	U. Trias	Otter	1981	Susp
Yanrey 1	51	NFW	22	15	16	114	34	57	GL	14	DF	16	431	Precamb	WAPET	1957	P & A
Yardie East 1	1968	NFW	22	00	28	113	55	34	GL	4	RT	11	5593	U.Trias	Mesa	1982	P & A
Yaringa 1	305	NFW	26	03	58	114	21	35	GL	21	KB	27	2288	Sil	COC	1966	P & A
Yarraloola 1	394	STR	21	23	07	115	45	52	GL	16	RT	17	272	L.Carb	WAPET	1967	P & A
Zeepard 1	1661	NFWO	20	44	14	114	25	22	WD	740	RT	10	4215	U.Trias	Esso	1980	P & A
Zeewulf 1	1492	NFWO	21	06	33	113	37	13	WD	1194	RT	10	3500	U.Trias	Esso	1979	P & A

Key to abbreviations used in Table 5.

GSWA 'S' No.

The 'S' number is the file number used by the Geological Survey of Western Australia for data pertaining to a given well.

Type—AAPG and API classification of wells.

EXT – Extension well
NFW – New field wildcat well
O – Offshore
NPW – New pool wildcat
STR – Stratigraphic test or structure well
DPT – Deeper pool test
SPT – Shallower pool test

This classification was established by Frederic H. Lahee; recent descriptions (Johnston, 1984) may be found in the AAPG Bulletin, v. 68, p. 1238–1239 and 1246.

Elevation

DF – Derrick floor
GL – Ground level
KB – Kelly bushing
RT – Rotary table
WD – Water depth (offshore wells)

Bottomed in

Camb – Cambrian
Carb – Carboniferous
Cret – Cretaceous
Dev – Devonian
Juras – Jurassic
Ord – Ordovician
Palaeo – Palaeozoic
Perm – Permian
Precamb – Precambrian
Sil – Silurian
Tert – Tertiary
Trias – Triassic
L – Lower
M – Middle
U – Upper

Company

Avon – Avon Engineering Pty Ltd
BMR – Bureau of Mineral Resources
Bond – Bond Corporation Pty Ltd
CNW – CNW Oil (Australia) Pty Ltd
COC – Continental Oil Co. of Australia Ltd
CSO – Canadian Superior Oil (Australia) Pty Ltd and Associated Companies
Esso – Esso Exploration and Production Australia Inc
Elvet – Elvet Exploration Pty Ltd
GWHYD – Golden West Hydrocarbons Pty Ltd
Hartog – Hartogen Explorations Pty Ltd
Hemat – Hematite Petroleum Pty Ltd
Hudbay – Hudbay Oil (Australia) Ltd
Mesa – Mesa Australia Ltd
Monarc – Monarch Petroleum N.L.
MPA – Marathon Petroleum Australia Ltd
Ocean – Ocean Ventures Pty Ltd
OFFO – Offshore Oil N.L.
OPPL – Oceania Petroleum Pty Ltd
Otter – Otter Exploration N.L.
Oxy – Australian Occidental Petroleum Inc.
Pancon – Pancontinental Petroleum Ltd
Phllps – Phillips Australian Oil Company
WAPET – West Australian Petroleum Pty Ltd
Wesmin – Wesminco Oil Pty Ltd
Wood – Woodside Petroleum Development Pty Ltd (formerly Bocal Pty Ltd)

Status

Abd – abandoned
Comp – completed
C – condensate
G – gas
O – oil
P – plugged
P & A – plugged and abandoned
Re-ent – suitable for re-entry
SI – shut in
Susp – suspended
W. Well – water well

TABLE 6. SUMMARY OF GROUNDWATER POTENTIAL OF MAJOR UNITS IN THE CARNARVON BASIN

Age	*Formation*	*Approx. max. thickness (m)*	*Comments*
HOLOCENE	Coastal dunes	10	Minor aquifer; small supplies; fresh to brackish; freshwater occurs as lenses overlying seawater and may become brackish or salty if overpumped.
	River-bed sands	10	Major aquifer in Gascoyne River and some other rivers; small to large supplies; generally fresh; temporary aquifers which may become exhausted if there is a long period between river flows.
	Alluvium	45	Major aquifer on coastal lowland; small to large supplies; fresh to saline but mainly brackish; freshwater generally occurs adjacent to major rivers.
	Hamelin Coquina	10	Local aquifer; small supplies; locally fresh underlain by saline water.
	Bundera Calcarenite	25	Minor aquifer; large supplies; fresh to brackish; karstic.
PLEISTOCENE	Tamala Limestone	300 +	Local aquifer; small supplies; fresh to brackish; supplies probably obtained from perched water tables.
	Peron Sandstone	120	No known groundwater abstraction; probably moderate to large supplies; saline.
	Exmouth Sandstone	100 +	Minor aquifer; small to moderate supplies; fresh to brackish.
TERTIARY	Trealla Limestone	55	Minor aquifers; small to large supplies; generally brackish to saline; fresh in elevated areas; locally karstic.
	Tulki Limestone	120	As above.
	Mandu Limestone	240	As above.
	Giralia Calcarenite	225	As above.
	Cardabia Calcarenite	80	As above.
CRETACEOUS	Korojon Calcarenite	45	No known groundwater abstraction; probable small supplies in subcrop/weathered outcrop.
	Toolonga Calcilutite	275	No known groundwater abstraction; probably local aquifer where weathered and silicified and also from rare interbeds of fine sandstone (*eg.* Rocky Pool); small supplies; generally brackish to saline.

TABLE 6. SUMMARY OF GROUNDWATER POTENTIAL OF MAJOR UNITS IN THE CARNARVON BASIN (continued)

Age	*Formation*	*Approx. max. thickness (m)*	*Comments*
CRETACEOUS	Gearle Siltstone	345	No known groundwater abstraction; possible small supplies in subcrop/weathered outcrop.
	Windalia Radiolarite	125	Local aquifer in weathered outcrop, subcrop and in deep bores; small to moderate supplies; occasionally artesian; brackish to brine.
	Muderong Shale	75	Local aquifer (Peedamullah Shelf) from thin interbeds of greensand; small to moderate supplies; locally artesian; brackish to saline.
	Birdrong Sandstone	35	Major aquifer; moderate to large supplies; commonly artesian; minor freshwater near outcrop; generally brackish to saline.
	Yarraloola Conglomerate	45	Minor aquifer eastern margin Peedamullah Shelf; small to moderate supplies; fresh adjacent to major rivers, elsewhere brackish to saline.
	Nanutarra Formation	75	As above.
TRIASSIC	Kockatea Shale	15	Aquiclude except where weathered and silicified or where it contains thin interbeds of sand; small supplies brackish to saline.
PERMIAN	Binthalya Formation	545	No known groundwater abstraction possibly small supplies but generally too elevated to be an aquifer; minor springs (Maslen spring); fresh to brackish.
	Mungadan Sandstone	60	Local aquifer; probably small supplies; source of numerous springs but generally too elevated to be a major aquifer; fresh to brackish.
	Coolkilya Sandstone	215	Local aquifer; moderate to small supplies in outcrop; minor springs (*eg.* Birdrong Spring); fresh to brackish.
	Baker Formation	90	No known groundwater abstraction; probably local aquifer; small supplies in outcrop; probably fresh to brackish.
	Nalbia Sandstone	120	Local aquifer; small to moderate supplies; fresh to brackish.
	Wandagee Formation	244	Local aquifer; small supplies in outcrop; fresh to brackish.
	Quinannie Shale	120	Aquiclude; possible source of saline groundwater from weathering of evaporite minerals in outcrop.
	Cundlego Formation	410	Minor aquifer; small to large supplies (1600 m^3/d); generally brackish.

TABLE 6. SUMMARY OF GROUNDWATER POTENTIAL OF MAJOR UNITS IN THE CARNARVON BASIN (continued)

Age	*Formation*	*Approx. max. thickness (m)*	*Comments*
PERMIAN	Bulgadoo Shale	520	Aquiclude; possible source of saline groundwater from weathering of evaporite minerals in outcrop.
	Mallens Sandstone	180	Major aquifer; numerous bores and wells, small to large supplies (2000 m^3/d); fresh to saline.
	Coyrie Formation	400	Local aquifer; small supplies in outcrop; fresh to saline.
	Keogh Formation	75	Minor aquifer; numerous bores and wells; moderate to large supplies; fresh to brackish.
	Billidee Formation	150	Local aquifer; small supplies outcrop; fresh to brackish.
	Moogooloo Sandstone	130	Major aquifer; numerous bores and wells in outcrop; moderate to large supplies (742 m^3/d); fresh to brackish.
	Cordalia Sandstone	60	Local aquifer; small supplies in outcrop; fresh to brackish.
	Callytharra Formation	265	Local aquifer; small supplies in outcrop; fresh to saline.
	Carrandibby Formation (Lyons Group)	70	Local aquifer; small supplies outcrop; fresh to brackish.
	Lyons Group	1480	Local aquifer depending on topography and stratigraphy; very extensive; numerous bores and wells, small to moderate supplies in outcrop; fresh to saline.
CARBONIFEROUS	Harris Sandstone (Lyons Group)	85	Local aquifer; small supplies in outcrop; fresh to saline.
	Yindagindy Formation	115	Local aquifer; small supplies in outcrop; probably fresh to saline.
	Williambury Formation	340	as above.
	Moogooree Limestone	400	as above.
DEVONIAN	Willaraddie Formation	295	as above.
	Munabia Sandstone	555	Minor aquifer; small supplies in outcrop; fresh to brackish.
	Gneudna Formation	820	Local aquifer; small supplies in outcrop; fresh to brackish.
	Nannyarra Sandstone	60	Local aquifer; small supplies in outcrop; fresh to brackish.

TABLE 6. SUMMARY OF GROUNDWATER POTENTIAL OF MAJOR UNITS IN THE CARNARVON BASIN (continued)

Age	*Formation*	*Approx. max. thickness (m)*	*Comments*
	Sweeney Mia Formation	200	Aquiclude; possible source of saline groundwater from solution of evaporites.
	Kopke Sandstone	500	Possible major aquifer probably moderate supplies; probably brackish to saline from underlying and overlying evaporites.
SILURIAN			
	Dirk Hartog Formation	740	No known groundwater abstraction; possible source of saline groundwater from solution of evaporites; probably moderate supplies; probably saline.
	Tumblagooda Sandstone	3000	Major aquifer; small to large supplies (1820 m^3/d); unconfined and artesian; fresh to saline.
PRECAMBRIAN	Metamorphics; dolerite; gneiss; granite	—	Local aquifers depending on site-specific conditions; small supplies; fresh to brackish.

Footnotes to comments

Major = extensive, commonly utilized
Minor = limited extent and utilization
Local = occasional bores/wells in site-specific locations.

Large supply = " 100 m^3/d
Moderate supply = 5 to 100 m^3/d
Small supply = <5 m^3/d
(1600 m^3/d) = known yield

Fresh = <1000 mg/L T.D.S.
Brackish = 1000 to 6000 mg/L T.D.S.
Saline = > 6000 mg/L T.D.S.

TABLE 7. SELECTED GROUNDWATER ANALYSES FROM THE CARNARVON BASIN

Bore name	*Date*	*pH*	*Conductivity mS/m @ 25°C*	*TDS**	*Ca*	*Mg*	*Na*	*K*	CO_3	HCO_3	*Cl*	SO_4	NO_3	SiO_2	*F*	*B*	*Fe*	*Mn*	*Formation*
Doorawarrah homestead	1979	7.9	37	220C	29	10	29	5	nil	143	26	21	4	18	0.1	0.16	0.08	—	River-bed sand
Gnallabiddy Well (Middalya)	1979	7.8	214	1310C	107	47	275	9	nil	241	406	303	<1	20	0.4	—	—	—	River-bed sand
House Well (Ningaloo)	1975	7.9	12 600	7430E	124	288	2160	97	nil	302	3820	607	52	9	3.6	—	—	—	Coastal sand/calcrete
Corner Well (Mardie)	1979	6.9	68	390C	34	25	63	5	nil	184	93	48	3	22	0.3	0.19	—	—	Alluvium
Eurardy House Well	1977	6.9	178	990E	12	36	274	19	nil	79	479	53	1	49	0.1	0.34	—	—	Alluvium
Manberry House Well (No. 1)	1979	8.5	270	1560C	26	22	492	32	15	384	523	114	55	68	2.8	—	0.16	—	Alluvium/colluvium
Meeragoolia homestead	1979	7.7	318	1780C	68	61	471	4	nil	251	729	202	35	56	1.0	—	—	—	Alluvium
Mooka homestead bore	1979	7.0	296	1670C	70	60	426	17	nil	183	659	263	4	48	0.4	—	0.20	—	Alluvium
Mooka homestead river bore	1979	7.6	170	960C	60	36	216	12	nil	134	350	182	<1	22	0.2	—	1.3	—	Alluvium
Mongers Well	1977	8.4	24	150E	13	6	17	5	1	90	7	14	<1	32	0.4	0.10	—	—	Alluvium
North Bore (Eudamullah)	1976	8.0	1010	650E	71	32	94	5	nil	308	158	35	8	86	0.6	0.21	—	<0.02	Calcreted alluvium
Pimbie House	1979	8.0	488	2930C	88	92	791	71	nil	451	1240	288	24	66	1.1	—	—	—	Alluvium
Shearing Shed Well (Cooralya)	1979	8.3	697	4070C	118	118	1180	42	3	268	1840	408	93	71	0.6	—	0.16	—	Alluvium
Towrana House	1979	7.2	215	1160C	37	39	321	13	nil	267	412	120	49	17	0.6	—	—	—	Alluvium/colluvium
Woolshed Well (Mardie)	1979	7.2	279	1510C	74	84	356	14	nil	323	604	167	6	40	—	0.9	—	—	Alluvium
Wooramel homestead well	1977	8.0	61	360E	58	14	45	6	nil	235	58	30	2	38	0.8	0.28	—	—	Alluvium
MRD Bore Cooralya	1979	7.4	1480	8900C	313	413	2290	109	nil	28	4500	894	146	68	0.7	—	0.26	—	?Windalia Radiolarite
Two-mile Well (Mia Mia)	1978	7.6	389	2220E	78	59	646	17	nil	500	801	310	2	47	—	1.2	—	—	Windalia Radiolarite
Edagee Bore	1977	7.6	425	2520E	86	61	729	40	nil	287	1020	406	3	21	0.8	—	—	—	Birdrong Sandstone
Hamelin No. 1 Bore	1977	7.2	940	5720E	150	147	1730	84	nil	238	2760	732	5	29	0.8	—	—	—	Birdrong Sandstone
Kooraline artesian bore (Minilya)	1978	7.5	1310	8380E	111	43	2900	55	nil	409	3700	1240	2	27	1.6	—	—	—	Birdrong Sandstone
Point Petit Bore (Nanga)	1978	7.3	698	4180E	126	89	1250	68	nil	339	1920	490	1	46	0.6	—	—	—	Birdrong Sandstone
Warroora No. 1 Bore	1978	7.6	1280	7800E	178	68	2650	62	nil	268	3580	1240	2	24	1.6	—	—	—	Birdrong Sandstone
Callytharra Springs	1977	8.3	145	860E	31	33	200	15	nil	128	306	112	17	68	0.4	0.78	—	—	Moogooloo Sandstone
East Shed Bore (Mia Mia)	1978	7.7	104	650E	60	39	91	17	nil	409	93	32	37	89	1.1	0.32	—	—	Moogooloo Sandstone
Yalardy House supply well	1977	7.3	336	1930E	52	59	536	35	nil	268	789	207	44	47	0.7	—	—	—	Moogooloo Sandstone
Talisker No. 1 Bore	1977	6.4	1660	10 700E	230	504	2710	202	nil	18	5040	1600	2	38	0.3	—	—	—	Permian, ?Wooramel Gp.
Coondoo Outcamp Well	1976	8.0	2440	1510E	104	106	246	3	nil	467	528	89	15	81	1.1	0.60	—	<0.02	Lyons Group
Corktree Well (Lyons R)	1976	8.0	2270	1420E	89	66	281	6	nil	372	479	93	40	89	3.9	0.67	—	<0.02	Lyons Group
Death Trap Well (Lyons R)	1976	8.6	700	420E	31	36	63	2	18	226	87	14	15	58	0.5	0.31	—	<0.02	Lyons Group
Muggon Bore	1976	6.9	3230	1810E	75	92	416	33	nil	79	856	178	69	58	0.2	0.73	—	—	Lyons Group
Bibbawarra Bore	1971	—	—	4840C	270	120	1300	80	nil	210	2140	700	—	—	—	—	<0.1	<0.1	Tumblagooda Sandstone
Good Bore SE (Riverside)	1977	7.1	451	2630E	31	79	754	31	nil	64	1310	172	4	47	0.2	—	—	—	Tumblagooda Sandstone
Ellavalla No. 1 Bore	1977	8.3	449	2650E	68	98	704	42	nil	259	1120	305	56	62	0.8	—	—	—	—
Homestead Bore (Hill Springs)	1979	8.3	311	1900C	60	55	517	36	nil	381	671	209	58	70	1.4	—	—	—	—
Meadow No. 1 Bore	1977	6.1	2030	13 500E	240	465	3800	177	nil	27	6610	1590	3	13	0.2	—	—	—	
Two-mile Bore (Hill Springs)	1979	8.6	209	1280C	36	30	356	24	nil	326	434	109	27	78	1.2	—	—	—	—
Woodleigh No. 11 Bore	1977	7.1	901	5390E	150	142	1520	93	nil	217	2550	584	5	15	1	—	—	—	—

*TDS—Total dissolved solids; C—Calculation; E—Evaporation All chemical results and TDS reported in mg/L; analyses by Government Chemical Laboratories, Perth

TABLE 8. APPROXIMATE GROUNDWATER ABSTRACTION IN THE CARNARVON BASIN, 1984.

User	*Yield* ($m^3 \times 10^6\ m^3/y$)	*Salinity* (*mg/L TDS*)	*Formation*
Carnarvon	1.299	300	Alluvium
Carnarvon Irrigation (private)	2.169	300–1000	Alluvium
Carnarvon Irrigation (Government)	4.440	300–400	Alluvium
Gascoyne Junction	0.025	300–400	Alluvium
Onslow	0.197	250	Alluvium
Exmouth	0.709	1000–2000	Tertiary limestones
Exmouth–Learmonth defence facilities	0.20 est.	1000–3000	Tertiary limestones
Agnew–Clough Ltd	0.45 est.	5700	Birdrong Sandstone
Denham	0.067	4560	Birdrong Sandstone
Pastoral (confined)	50.00 est.	3000–6000	Birdrong Sandstone
Texada Mines	0.45 est.	500	Birdrong Sandstone
Kalbarri	0.285	300–400	Tumblagooda Sandstone
Pastoral (unconfined)	2.30 est.	500–6000	Various

est.—estimated

REFERENCES

AGOSTINI, M. D., 1983, Development of the North Rankin Field, North West Shelf, Australia: APEA Jour., v. 23, pt 1, p. 164–169.

ALLEN, A. D., 1972a, Cretaceous–Holocene stratigraphy and structure, lower Gascoyne River, Carnarvon Basin: West. Australia Geol. Survey Ann. Rept 1971, p. 22–25.

ALLEN, A. D., 1972b, Results of investigation into groundwater resources along the Lower Gascoyne River for Carnarvon Irrigation and Town Water Supplies: West. Australia Geol. Survey Record 1972/9.

ALLEN, A. D., 1972c, Groundwater resources along the Lower Gascoyne River — a summary: West. Australia Geol. Survey. Ann. Rept 1971, p. 16–22.

ALLEN, A. D., in press, An outline of the hydrogeology of the Carnarvon Basin: West. Australia Geol. Survey Rept.

ALEXANDER, R., KAGI, R., and WOODHOUSE, G., 1980, Origin of the Windalia Oil, Barrow Island, Western Australia: APEA Jour., v. 20, pt 1, p. 250–256.

ANDREJEWSKIS, A. J., 1969, Flinders Shoal No. 1 well completion report: West Australian Petroleum Pty. Ltd. report (unpublished).

ANNELS, A. E., 1984, The geotectonic environment of Zambian copper-cobalt mineralization: Geol. Soc. London Jour. v. 141, p. 279–290.

ANON, 1965, Review of Australia's water resources 1963: Dept. of National Development, Australian Water Resources Council.

ANON, 1976, Review of Australia's water resources 1975: Dept. of National Development, Australian Water Resources Council.

ANON, 1983, Groundwater system review, Kalbarri: West. Australian Public Works Dept., Report No. WRB32.

APTHORPE, M. C., 1979, Depositional history of the upper Cretaceous of the Northwest Shelf, based on Foraminifera: APEA Jour., v. 19, pt. 1, p. 74–89.

APTHORPE, M. C., 1981, Tertiary depositional history of the North West Shelf, Western Australia, *in* Sediments through the ages, Fifth Australian Geological Convention, Perth, 1981: Geol. Soc. Australia, Abstracts 3, p. 55.

ARCHBOLD, N. W., 1980, *Lingula* (Lingulidae, Brachiopoda) from the Late Artinskian (Permian), Carnarvon Basin, Western Australia: Royal Soc. Victoria, Proc., v. 92, pt 2, p. 169–180.

ARCHBOLD, N. W., 1981a, Fish scales from the Permian of Western Australia: Royal Soc. West. Australia, Jour. v. 4, pt 1, p. 23–26.

ARCHBOLD, N. W., 1981b, Studies on Western Australian Permian brachiopods: 2. The family Rugosochonetidae Muir-Wood 1962: Royal. Soc. Victoria Proc., v. 93, p. 109–128.

ARCHBOLD, N. W., 1981c, A new species of Tornquistia (Brachiopoda) Australia: Nat. Museum Victoria Mem. 42, p. 7–14.

ARCHBOLD, N. W., 1981d, *Svalbardia* (Chonetidina, Brachiopoda) from the Kungurian (Permian) of Western Australia: Alcheringa, v. 5, no. 1, p. 1–8.

ATKINSON, W. J., HUGHES, F. E., and SMITH, C. B., 1983, A review of the kimberlitic rocks of Western Australia: CRA Exploration Pty Ltd, report 130077 (unpublished).

ATKINSON, W. J., HUGHES, F. E., and SMITH, C. B., 1984, A review of kimberlitic rocks of Western Australia, *in* Kimberlites 1: Kimberlites and related rocks, *edited by* J. KORNPROBST: Elsevier, Amsterdam, p. 195–224.

BACKHOUSE, J., 1979, Palynology of samples from BHP boreholes, Mount Bruce sheet: West. Australia Geol. Survey Palaeontology Report no. 3/1979 (unpublished).

BALLEAU, W. P., 1973, The Pilbara Region — Outline of groundwater resources, 1973. West. Australia Geol. Survey Record 1973/21.

BALME, B. E., 1962, Upper Devonian (Frasnian) spores from the Carnarvon Basin, Western Australia: Paleobotanist, v. 9, p. 1–10.

BALME, B. E., 1966, Merlinleigh no. 1 well: Palaeontological report no. 242, (unpublished).

BALME, B. E., 1969, The Triassic system in Western Australia: APEA Jour., v. 9, pt 2, p. 67–78.

BANERJEE, I., 1966, Turbidites in a glacial sequence: a study from the Talchir Formation, Raniganj Coalfield, India: Jour. Geology, v. 74, no. 5, p. 593–606.

BARTLETT, W. M., 1983, Western Australia Year Book, no. 20, 1982: Australian Bureau of Statistics, Perth.

BASTIAN, L. V., and WILLMOTT, S. P., 1965, Completion Report, Stratigraphic Bore BMR 5, Giralia, Western Australia: Australia BMR Rept 84.

BATE, R. H., 1972, Upper Cretaceous Ostracoda from the Carnarvon Basin, Western Australia: Palaeontological Assoc. Spec. Paper 10.

BAXTER, J. L., 1967, Hydrogeological features of the Gascoyne River west of the Kennedy Range: West. Australia Geol. Survey Ann. Rept 1966, p. 44–45.

BAXTER, J. L., 1977, Heavy mineral sand deposits of Western Australia: West. Australia Geol. Survey Mineral Resources Bull. 10.

BEARD, J. S., 1975, Sheet 5, Pilbara: Vegetation survey of Western Australia 1:1 000 000 series, Univ. West. Australia Press, Nedlands.

BEARD, J. S., 1976a, Geraldton: Vegetation survey of Western Australia 1:250 000 series, Vegmap Publications, Applecross, W.A.

BEARD, J. S., 1976b, Ajana: Vegetation survey of Western Australia 1:250 000 series, Vegmap Publications, Applecross, W.A.

BEARD, J. S., 1976c, Shark Bay and Edel: Vegetation survey of Western Australia 1:250 000 series, Vegmap Publications, Applecross, W.A.

BEARD, J. S., 1976d, Sheet 6, Murchison: Vegetation survey of Western Australia 1:1 000 000 series, Univ. West. Australia Press, Nedlands.

BEARD, J. S., 1981, The vegetation of Western Australia at 1:3 000 000 scale, explanatory notes: West. Australia Forests Dept.

BELFORD, D. J., 1958, Stratigraphy and micropalaeontology of the Upper Cretaceous of Western Australia: Geol. Rundschau, v. 47, p. 629–647.

BELFORD, D. J., 1960, Upper Cretaceous Foraminifera from the Toolonga Calcilutite and Gingin Chalk: Australia BMR Bull. 57.

BELFORD, D. J., 1983, A probably Coniacian (Late Cretaceous) foraminiferal fauna, Carnarvon Basin, Western Australia: Australia BMR Bull. 217, p. 11–27.

BELFORD, D. J., and SCHEIBNEROVA, V., 1972, Thornian foraminifera from the Carnarvon Basin, Western Australia, and their palaeogeographical significance: Micropaleontology, v. 17, pt 3, p. 331–344.

BERVEN, R. J., 1969, Remarkable Hill No. 1 well completion report: Marathon Petroleum Pty. Ltd. report (unpublished).

BESTOW, T.T., 1969, The assessment and utilization of the underground water resources of Western Australia: Institution of Engineers of Australia, Perth, September 22, 1969.

BESTOW, T. T., 1982, The potential for geothermal energy development in Western Australia: West Australia Geol. Survey Record 1982/6.

BOURGEOIS, J, 1980, A transgressive shelf sequence exhibiting hummocky stratification: the Cape Sebastian Sandstone (Upper Cretaceous), southwestern Oregon: Jour. Sedimentary Petrology, v. 50, no. 3, p. 681–702.

BOWERING, O. J. W., 1968, Hope Island no. 1 well completion report: West. Australian Petroleum Pty Ltd report (unpublished).

BOWLER, J. M., 1976, Aridity in Australia: age, origins and expression in aeolian landforms and sediments: Earth Science Review, v. 12, p. 279–310.

BOWLER, J. M., and JONES, R., 1979, Australia was a land of lakes: Geographical magazine, v. 51, no. 10, p, 679–685.

BOWLER, J. M., HOPE, G. S., JENNINGS, J. N., SINGH, G., and WALKER, D., 1976, Late Quaternary climates of Australia and New Guinea: Quaternary Research 6, p. 359–394.

BRANSON, J. C., 1974, Structures of the western margin of the Australian continent: Oil and Gas (Sydney), v. 20, no. 9, p. 24–35.

BRIKKE, I. 1982, Geochemical interpretation of some oils and condensates from the Dampier Sub-basin of Western Australia: APEA Jour., v. 22, pt 1, p. 179–187.

BROMLEY, R. G., 1967, Marine phosphorites as depth indicators: Marine Geology, v. 5, p. 503–510.

BROOK, G. A., and FORD, D. C., 1978, The origin of labyrinth and tower karst and the climatic conditions necessary for their development: Nature, v. 275, p. 493–496.

BROWN, S. A., BOSERIO, I. M., JACKSON, K. S., and SPENCE, 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: Proceedings of Geol. Soc. Australia/Petroleum Expl. Soc. Australia Symposium, Perth, 1984, p. 85–96.

BROWNHILL, M. H., 1966, Report on Merlinleigh Anticline structural drilling: West. Australian Petroleum Pty Ltd report (unpublished).

BROWNHILL, M. H., 1967, Sholl No. 1 well completion report: West. Australian Petroleum Pty Ltd report (unpublished).

BRUNNSCHWEILER, R. O., 1961, On echinoids in the Tertiary of Western Australia with a description of two new Eocene Fibulariidae: Geol. Soc. Australia Jour. v. 8, no. 2, p. 159–169.

BRUNNSCHWEILER, R. O., 1966, Cretaceous ammonites of Western Australia, I: the heteromorph *Lytoceratina*: Australia BMR Bull. 58.

BUTCHER, B. P., van de GRAAFF, W. J. E., and HÖCKING, R. M., 1984, Shark Bay–Edel, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

CAMPBELL, I. R., and SMITH, D. N., 1982, Gorgon 1—southernmost Rankin Platform gas discovery: APEA Jour., v. 22, pt 1, p. 102–111.

CAMPBELL, I. R., TAIT, A. M., and REISSER, R. F., 1984, Barrow Island Oilfield, revisited: Australian APEA. Jour., v. 24, pt 1, p. 289–298.

CANDE, S. C., and MUTTER, J. C., 1982, A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica: Earth and Planetary Sci. Letters, v. 58, p. 151–160.

CARPENTER, A. B., 1978, Origin and chemical evolution of brines in sedimentary basins: Oklahoma Geol. Survey Circ. 79, p. 60–77.

CARTER, J. D., 1981: Uranium exploration in Western Australia: West. Australia Geol. Survey Record 1981/6.

CHAMBERLAIN, N. G., DOOLEY, J. C., and VALE, K. R., 1954, Geophysical exploration in the Carnarvon (N.W.) Basin, Western Australia: Australia BMR Record 1954/44.

CHAPRONIERE, G. C. H., 1975, Palaeoecology of Oligo-Miocene larger Foraminiferida, Australia: Alcheringa, v. 1, p. 37–58.

CHAPRONIERE, G. C. H., 1976, The Bullara Limestone, a new rock-stratigraphic unit from the Carnarvon Basin, Western Australia: BMR Jour. Australian Geology Geophysics, v. 1, p. 171–174.

CHAPRONIERE, G. C. H., 1984, Oligocene and Miocene larger Foraminiferida from Australia and New Zealand: Australia BMR Bull. 188.

CLAPP, F. G., 1925, A few observations on the geology and geography of the North-West and Desert Basins, Western Australia: Linnean Soc. New South Wales Proc., v. 50, p. 4766.

CLAPP, F. G., 1926a, The oil problem of Western Australia: Economic Geology, v 21, pt 5, p. 409–430.

CLAPP, F. G., 1926b, Oil prospects of the North West Basin of Western Australia: Amer. Assoc. Petroleum Geol. Bull., v. 10, pt 11, p. 1136–1149.

CLARK, F. E., 1979, Upper Cretaceous foraminifera and biotstratigraphy of C-Y Creek, Western Australia: Carleton University, Ottawa, Canada, M.Sc. Thesis (unpublished).

CLARKE, E. de C. and TEICHERT, C., 1948, Cretaceous stratigraphy of Lower Murchison River area, Western Australia: Royal Soc. West. Australian Jour., v. 32, p. 19–48.

COCKBAIN, A. E., 1974, Triassic conchostracans from the Kockatea Shale: West. Australia Geol. Survey Ann. Rept. 1973, p. 104–106.

COCKBAIN, A. E., 1980, Permian ammonoids from the Carnarvon Basin—a review: West. Australia Geol. Survey Ann. Rept. 1979, p. 100–105.

COCKBAIN, A. E., 1981, On the age of the Merlinleigh Sandstone, Carnarvon Basin: West. Australia Geol. Survey Ann. Rept. 1980, p. 44–46.

COCKBAIN, A. E., 1985, Devonian stromatoporoids from the Carnarvon Basin, Western Australia: Ludbrook Honour Volume, South Australia Dept Mines and Energy, p. 29–34.

COLEMAN, J. M., 1969, Brahmaputra River: channel processes and sedimentation: Sedimentary Geology, v. 3, p. 129–239.

CONDIT, D. D., 1935, Oil possibilities in the North West district, Western Australia: Economic Geology, v. 30, pt. 8, p. 860–878.

CONDIT, D. D., RAGGATT, H. G., and RUDD, E. A., 1936, Geology of the North West Basin, Western Australia: Amer. Assoc. Petroleum Geol. Bull., v. 20, pt 8, p. 1028–1070.

CONDON, M. A., 1954, Progress report on the stratigraphy and structure of the Carnarvon Basin, Western Australia: Australia BMR Rept. 15.

CONDON, M. A., 1955, Minilya, 4 mile Geological Series: Australia BMR Explan. Notes Series 4.

CONDON, M. A., 1962a, Kennedy Range, Western Australia: Australia BMR 1:250 000 Geol. Series Explan. Notes.

CONDON, M. A., 1962b, Glenburgh, Western Australia: Australia BMR 1:250 000 Geol. Series Explan. Notes.

CONDON, M. A., 1965a, Wooramel, Western Australia: Australia BMR 1:250 000 Geol. Series Explan. Notes.

CONDON, M. A., 1965b, The geology of the Carnarvon Basin, Western Australia, Part 1: Pre-Permian stratigraphy: Australia BMR Bull. 77.

CONDON, M. A., 1967, The geology of the Carnarvon Basin, Western Australia, Part 2: Permian stratigraphy: Australia BMR Bull. 77.

CONDON, M. A., 1968, The geology of the Carnarvon Basin, Western Australia, Part 3: Post-Permian stratigraphy; structure; economic geology: Australia BMR Bull. 77.

CONDON, M. A., JOHNSTONE, D., PERRY, W. J., and CRESPIN, I., 1953, The Cape Range structure, Western Australia: Australia BMR. Bull. 21, (1st edition).

CONDON, M. A., JOHNSTONE, D., PERRY, W. J., and CRESPIN, I., 1955, The Cape Range structure, Western Australia: Australia BMR. Bull. 21, (2nd edition).

CONDON, M. A., JOHNSTONE, D., PRITCHARD, C. E., and JOHNSTONE, M. H., 1956, The Giralia and Marrilla Anticlines, North-west Division, Western Australia: Australia BMR Bull. 25.

CONNOLLY, R. R., 1960, Report on inspection of Temporary Reserve 1632H and others for gypsum, Boologooro, N. W. Division: West. Australia Geol. Survey Ann. Rept 1958, p. 23–24.

CONTINENTAL OIL COMPANY OF AUSTRALIA LTD, 1968, Hamelin Pool No. 1, W.A., well completion report (unpublished).

COOK, A. C., and KANTSLER, A. J., 1980, The maturation history of the epicontinental basins of Western Australia: U.N. ESCAP, CCOP/SOPAC Tech. Bull. 3, p. 171–195.

COOK, A. C., SMYTH, M., and VOS, R. G., 1985, Source potential of Upper Triassic fluvio-deltaic systems of the Exmouth plateau: APEA Jour., v. 25, pt 1, p. 204–215.

COWAN, W., 1968, Peedamullah No. 1 well completion report: West. Australian Petroleum Pty Ltd report (unpublished).

COX, L. R., 1961, The molluscan fauna and probable Lower Cretaceous age of the Nanutarra Formation of Western Australia: Australia BMR Bull. 61, p. 1–52.

CRAIG, E., 1950, Structures of the North-west Basin in Western Australia: World Oil, v. 130, no. 4, p. 210–214.

CRANK, K. A., 1973, Geology of Barrow Island oilfield: APEA Jour., v. 13, p. 49–57.

CRANK, K. A., 1980, Petroleum exploration in Western Australia in 1979: West. Australia Geol. Survey Ann. Rept 1979, p. 40–45.

CRESPIN, I., Indo-Pacific influences in Australian Tertiary foraminiferal assemblages: Royal Soc. South Australia Trans., v. 72, p. 134–142.

CRESPIN, I., 1950, Australian Tertiary microfaunas and their relationship with assemblages elsewhere in the Pacific region: Jour. Paleontology, v. 24, no. 4, p. 421–429.

CRESPIN, I., 1953, Micropalaeontology, *in* The Cape Range structure, Western Australia: Australia BMR Bull. 21, pt 2, p. 43–75, (1st edition).

CRESPIN, I., 1955, Micropalaeontology, *in* The Cape Range structure, Western Australia: Australia BMR Bull. 21, pt 2, p. 49–82, (2nd edition).

CROSTELLA, A., and BARTER, T. P., 1980, Triassic-Jurassic depositional history of the Dampier and Beagle Subbasins, Northwest Shelf of Australia: APEA Jour., v. 20, pt 1, p. 25–33.

CROSTELLA, A., and CHANEY, M. A., 1978, The petroleum geology of the outer Dampier Sub-basin: APEA Jour., v. 18, pt 1, p. 13–22.

CROWELL, J. C., and FRAKES, L. A., 1971, Late Palaeozoic glaciation of Australia: Geol. Soc. Australia Jour., v. 17, no. 2, p. 115–155.

DAHLKAMP, F. J., 1978, A classification of uranium deposits: Mineralium Deposita, v. 113, p. 83–104.

DAMPIER MINING COMPANY, 1973, Temporary Reserve 5659H, Glenburgh area, Byro Basin, Western Australia: report (unpublished).

DAVIDSON, W. A., 1975, Hydrogeological reconnaissance of the northwest Pilbara region: West. Australia Geol. Survey Record 1975/12.

DAVIES, G. R., 1970, Carbonate bank sedimentation, eastern Shark Bay, Western Australia: Amer. Assoc. Petrol. Geologists Mem. 13, p. 85–168.

de la HUNTY, L. E., 1965, Mount Bruce, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

DEE, T. W. H., and RUDD, E. A., 1932, Report of investigations, geological survey, Wooramel River area, Western Australia: Oil Search Ltd report (unpublished).

DENMAN, P. D., and van de GRAAFF, W. J. E., 1977 Emergent Quaternary marine deposits in the Lake MacLeod area, Western Australia: West Australia Geol. Survey Ann. Rept 1976, p. 32–37.

DENMAN, P. D., and van de GRAAFF, W. J. E., 1982, Quobba, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

DENMAN, P. D., HOCKING, R. M., MOORE, P. S., WILLIAMS, I. R., and van de GRAAFF, W. J. E., 1985, Wooramel, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

de RAAFF, J. F. M., BOERSMA, J. R., and van GELDER, A., 1977, Wave generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland: Sedimentology, v. 24, p. 451–484.

DEVLIN, S. P., 1983, Final report on exploration licences 09/12 Weer Dam, 09/13 Barrabiddy, 09/25 Billamberry, South, 09/26 Billamberry, and exploration licence applications 09/17 Manberry, 09/23 Barrabiddy 1, Merlinleigh Basin, W.A., Winning Pool SF50–13, Kennedy Range SF50–1: CRA Exploration Pty Ltd report (unpublished).

DICKINS, J. M., 1956, Permian pelecypods from the Carnarvon Basin, Western Australia: Australia BMR Bull. 29.

DICKINS, J. M., 1957, Pelecypods and gastropods from the Lyons Group, Carnarvon Basin, Western Australia: Australia BMR Bull. 41, p. 14–52.

DICKINS, J. M., 1963, Permian pelecypods and gastropods from Western Australia: Australia BMR Bull. 63.

DICKINS, J. M. 1978, Climate of the Permian in Australia: the invertebrate faunas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 23, p. 33–46.

DICKINS, J. M., 1985, Late Palaeozoic glaciation: BMR Jour. Australian Geology Geophysics, v. 9, p. 163–169.

DICKINS, J. M., and THOMAS, G. A., 1959, The marine fauna of the Lyons Group and the Carandibby Formation of the Carnarvon Basin, Western Australia: Australia BMR Rept 38, p. 65–96.

DOE, T. W. and DOTT, R. H. jnr., 1980 Genetic significance of deformed cross-bedding — with examples from the Navajo and Weber Sandstones of Utah: Jour. Sedimentary Petrology., v. 50, no. 3, p. 793–812.

DOLBY, J. H., and BALME, B. E., 1976, Triassic palynology of the Carnarvon Basin. Western Australia: Review Palaeobotany Palynology, v. 22, no. 2, p. 105–168.

DOTT, R. H. jnr., 1964, Wacke, greywacke and matrix — what approach to immature sandstone classification?: Jour. Sedimentary Petrology, v. 34, p. 625–632.

DRING, R. S., 1980, Palaeobiology of the Gneudna Formation, Late Devonian (Frasnian), Carnarvon Basin, Western Australia: West. Australia Univ. Ph.D. Thesis (unpublished).

EDGELL, H. S., 1952, The micropalaeontology of the Giralia Anticline, N.W. Australia: Australia BMR Record 1952/75 (unpublished).

EDGELL, H. S., 1957, The genus *Globatruncana* in North-west Australia: Micropaleontology, v. 3, no. 2, p. 101–126.

EDGELL, H. S., 1964, Triassic ammonite impressions from the type section of the Minchin Siltstone, Perth Basin: West. Australia Geol. Survey Ann. Rept 1963, p. 55–57.

EDWARDS, A. B., 1952, Sandstones from the North-west Basin, Western Australia: Australia CSIRO Rept 498.

EDWARDS, M. B., 1978, Glacial environments; *in* Sedimentary environments and facies *edited by* H. G. READING: Blackwell Sci. Pub., London, p. 416–438.

ELLIOTT, R. M. L., IASKY, R. P., and CRANK, K. A., 1985, Review of petroleum exploration in Western Australia to the end of 1984: West. Australia Geol. Survey Record 1985/2.

ELLIOTT, T., 1978a, Clastic Shorelines, *in* Sedimentary environments and facies, *edited by* H. G. READING: Blackwell Sci. Pub., London, p. 143–177.

ELLIOTT, T., 1978b, Deltas, *in* Sedimentary environments and facies, *edited by* H. G. READING, Blackwell Sci. Pub., London, p. 97–142.

EMBLETON, B. J. J., 1973, The palaeolatitude of Australia through Phanerozoic time: Geol. Soc. Australia Jour. v. 19, p. 475–482.

EXON, N. F., and WILLCOX, J. B., 1978, The geology and petroleum potential of the Exmouth Plateau of Western Australia: Amer. Assoc. Petroleum Geol. Bull., v. 62, pt 1, p. 40–72.

EXON, N. F. and WILLCOX, J. B., 1980, The Exmouth Plateau: stratigraphy, structure and petroleum potential: Australia BMR Bull. 199.

FAIRBRIDGE, R. W., 1953a, The Sahul Shelf, Northern Australia: its structure and geological relationships: Royal Soc. West Australia Jour., v. 37, p. 1–33.

FAIRBRIDGE, R. W., 1953b, Australian stratigraphy: Univ. West Australia Text Books Board, p. 516.

FALVEY, D. A. 1974, The development of continental margins in plate tectonics theory: APEA Journal., v. 14, pt 1, p. 95–106.

FALVEY, D. A., and MUTTER, J. C., 1981, Regional plate tectonics and the evolution of Australia's passive continental margins: BMR Jour. Australian Geology Geophysics, v. 6, p. 1–29.

FALVEY, D. A., and VEEVERS, J. J., 1974, Physiography of the Exmouth and Scott Plateau, Western Australia and adjacent northeast Wharton Basin: Marine Geology, v. 17, p. 21–59.

FINKL, C. W. jnr., and CHURCHWARD, H. M., 1973, The etched land surfaces of southwestern Australia: Geol. Soc. Australia Jour., v. 20, p. 295–308.

FLINT, R. F., 1971, Glacial and Quaternary Geology: Wiley, New York.

FORTH, J. R., 1973, Exmouth water supply: West. Australia Geol. Survey Ann. Rept 1972, p. 11–15.

FOSTER, R. J., and PHILIP, G. M., 1978, Tertiary holasteroid echinoids from Australia and New Zealand: Palaeontology, v. 21, p. 791–822.

FRAKES, L. A., and CROWELL, J. C., 1969, Late Paleozoic glaciation: I, South America: Geol. Soc. Amer. Bull. v. 80, p. 1007–1042.

FRASER, A. R., and TILBURY, L. A., 1979, Structure and stratigraphy of the Ceduna Terrace region, Great Australian Bight: APEA Jour., v. 19, pt 1, p. 53–65.

FRYE, L. C., and WILLMAN, H. B., 1962, Morphostratigraphic units in Pleistocene stratigraphy — Note 27, stratigraphic commission: Amer. Assoc. Petroleum Geol. Bull., v. 46, p. 112–113.

GEARY, J. K., 1970, Offshore exploration of the southern Carnarvon Basin: APEA Jour., v. 10, pt 2, p. 9–15.

GEARY, J. K., and GARRETT, R. D., 1970, Well completion report Pendock ID No. 1: Canadian Superior Oil (Aust.) Pty Ltd report (unpublished).

GENOA OIL N. L., 1970, Final report on Pendock ID No. 1 well, Western Australia: report (unpublished).

GENTILLI, J., and FAIRBRIDGE, R. W., 1951, Physiographic diagram of Australia: Columbia University Geographical Press, New York.

GLENISTER, B. F., and FURNISH, W. M., 1961, The Permian ammonoids of Australia: Jour. Paleontology, v. 35, p. 673–736.

GLENISTER, B. F., and GLENISTER, A. T., 1957, Discovery of Silurian strata from Western Australia: Australian Jour. Sci., v. 20, p. 115–116.

GLENISTER, B. F., and GLOVER, J. E., 1958, *Teichertia* in the Plantagenet Beds of Western Australia: Roy. Soc. West. Australia Jour., v. 41, p. 84–87.

GLENISTER, B. F., MILLER, A. K., and FURNISH, W. M., 1956, Upper Cretaceous and early Tertiary nautiloids from Western Australia: Jour. Paleontology, v. 30, p. 492–503.

GOULD, K. W., and SMITH, J. W., 1978, Isotopic evidence for microbiologic role in genesis of crude oil from Barrow Island: Amer. Assoc. Petroleum Geol. Bull., v. 62, p. 445–462.

GREGORY, C. V., 1982, Final report on exploration completed within Mineral Claims 08/2873–2876 and 3171–3182, Mia Mia, Winning Pool, Western Australia: CRA Exploration Pty Ltd report (unpublished).

GREY, K., van de GRAAFF, W. J. E., and HOCKING, R. M., 1977, Precambrian stromatolites as provenance indicators in the Permian Lyons Formation: West. Australia Geol. Survey Ann. Rept 1976, p. 70–72.

HAMBLIN, W. K., 1965, Origin of "reverse drag" on the downthrown side of normal faults: Geol. Soc. Amer. Bull., v. 76, p. 1145–1164.

HARLAND, W. B., COX, A. V., LLEWELLYN, P. G., PICKTON, C. A. G., SMITH, A. G., and WALTERS, R., 1982, A geologic time scale: Cambridge University Press, Cambridge, 131p.

HARMS, J. C., SPEARING, D. R., SOUTHARD, J. B., and WALKER, R. G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Soc. Econ. Paleontologists and Mineralogists Short Course 2, Tulsa, Oklahoma, 161p.

HARMS, J. E., and MORGAN, B. D., 1964, Pisolitic limonite deposits in Northwest Australia: Australian Inst. Mining Metall. Proc., no. 212, p. 91–124.

HARRIS, E. J., 1978, The production geology of the North Rankin gas field, Australia: Amer. Assoc. Petroleum Geol. Bull., v. 62, pt 7, p. 1219–1220.

HARRISON, P. H., 1979, Temporary reserves 6842H and 6843H, Cardabia, Final report of work completed to 26th October 1979: International Nickel Australia Ltd Report (unpublished).

HARRISON, P. H., 1985, An evaluation of the mineral potential of the onshore Carnarvon Basin: West. Australia Geol. Survey Record 1984/8.

HEATH, R. S., and APTHORPE, M. C., 1981, Tertiary foraminiferal biostratigraphy of the North West Shelf, Western Australia: Fifth Australian Geol. Convention, Perth, 1981, Geol. Soc. Australia, Abstracts 3, p. 68.

HEATH, R. S., and APTHORPE, M. C., 1984, New formation names for the Late Cretaceous and Tertiary sequence of the southern North West Shelf: West. Australia Geol. Survey Record 1984/7.

HECKEL, P. H., 1972, Recognition of ancient shallow marine environments: Soc. Economic Paleontologists and Mineralogists Spec. Pub. 16, p. 226–286.

HELBY, R., MORGAN, R., and PARTRIDGE, A. D., 1987, A palynological zonation of the Australian Mesozoic: Association of Australian Palaeontologists, Mem. 4.

HEMATITE PETROLEUM PTY LTD, 1972a, Cane River No. 1 well completion report (unpublished).

HEMATITE PETROLEUM PTY LTD, 1972b, Completion report Cane River Nos. 2, 3, 4 and 5 (unpublished).

HENDERSON, R. A., and McNAMARA, K. J., 1985a, Maastrichtian non-heteromorph ammonites from the Miria Formation, Western Australia: Palaeontology, v. 28, p. 35–88.

HENDERSON, R. A., and McNAMARA, K. J., 1985b, Taphonomy and ichnology of cephalopod shells in a Maastrichtian chalk from Western Australia: Lethaia, v. 18, p. 305–322.

HENDERSON, S. W., and SHANNON, P. H., 1966, Yaringa No. 1 well, Western Australia, stratigraphic drilling project; well completion report: Continental Oil Co. Australia Ltd (unpublished).

HEWARD, A. P., 1978, Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Cinera-Matallena and Sabero) coalfields, northern Spain: Sedimentology, v. 25, p. 451–488.

HEWGILL, F. R., KENDRICK, G. W., WEBB, R. J., and WYRWOLL, K. H., 1983, Routine ESR dating of emergent Pleistocene marine units in Western Australia: Search, v. 14, no. 7–8, p. 215–217.

HILL, D., 1954, Coral faunas from the Silurian of New South Wales and the Devonian of Western Australia: Australia BMR Bull. 23.

HOCKING, R. M., 1979, Sedimentology of the Tumblagooda Sandstone (Silurian) in the lower Murchison River area, Western Australia: a preliminary interpretation: West. Australia Geol. Survey Ann. Rept 1978, p. 40–44.

HOCKING, R. M., 1981, The Tumblagooda Sandstone, Western Australia: its type section and sedimentology: West. Australia Geol. Survey Ann. Rept 1980, p. 53–61.

HOCKING, R. M., 1985, Revised stratigraphic nomenclature in the Carnarvon Basin, W.A.: West. Australia Geol. Survey Record 1985/6.

HOCKING, R. M., and van de GRAAFF, W. J. E., 1978, Cretaceous stratigraphy and sedimentology, northeastern margin of the Carnarvon Basin, Western Australia: West. Australia Geol. Survey Ann. Rept 1977, p. 36–41.

HOCKING, R. M., MOORE, P. S., and MOORS, H. T., 1980, Modified stratigraphic nomenclature and concepts in the Palaeozoic sequence of the Carnarvon Basin, W.A.: West. Australia Geol. Survey Ann. Rept 1979, p. 51–55.

HOCKING, R. M., van de GRAAFF, W. J. E., BLOCKLEY, J. G., and BUTCHER, B. P., 1983, Ajana, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

HOCKING, R. M., WILLIAMS, S. J., LAVARING, I. H., and MOORE, P. S., 1985, Winning Pool–Minilya, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

HOCKING, R. M., WILLIAMS, S. J., MOORE, P. S., DENMAN, P. D., LAVARING, I. H., and van de GRAAFF, W. J. E., 1985, Kennedy Range, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

HOSEMANN, P., and PARRY, J., 1967, Locker No. 1 well completion report: West. Australian Petroleum Pty. Ltd. report (unpublished).

HOWARD, J. D., 1966, Characteristic trace fossils in Upper Cretaceous sandstones of the Book Cliffs and Wasatch Plateau, central Utah: Utah Geol. Min. Survey Bull., v. 8, p. 35–53.

HSU, K. J., 1972, Origin of saline giants: a critical review after the discovery of the Mediterranean Evaporite: Earth Science Reviews, v. 8, p. 371–396.

JACKSON, M. J., and van de GRAAFF, W. J. E., 1981, The Geology of the Officer Basin, Western Australia: Australia BMR Bull. 206.

JACKSON, S. A., and BEALES, F. W., 1967, An aspect of sedimentary basin evolution—The concentration of Mississippi Valley-type ores during late stages of diagenesis: Bull. Canadian Petroleum Geology, v. 15, no. 4, p. 383–433.

JAQUES, A. L., LEWIS, J. D., and SMITH, C. B., 1986, The Kimberlites and Lamproites of Western Australia: West. Australia Geol. Survey Bulletin 132.

JENNINGS, J. N., 1975, Desert dunes and estuarine fill in the Fitzroy Estuary, north western Australia: Catena, v. 2, p. 215–262.

JOHNSON, D. P., 1974, Sedimentation in the Gascoyne River delta, Western Australia: Univ. West. Australia Ph. D. Thesis (unpublished).

JOHNSON, D. P., 1982, Sedimentary facies of an arid zone delta: Gascoyne Delta, Western Australia: Jour. Sedimentary Petrology, v. 52, no. 2, p. 547–563.

JOHNSON, H. D., 1978, Shallow siliciclastic seas, *in* sedimentary environments and facies, *edited by* H. G. READING, Blackwell, London, p. 207–258.

JOHNSTON, R. R., 1984, North American Drilling Activity in 1983: Amer. Assoc. Petroleum Geol. Bull., v. 68, p. 1234–1265.

JOHNSTONE, D., CONDON, M. A., and PLAYFORD, P. E., 1958, The stratigraphy of the Lower Murchison River area and Yaringa North Station, Western Australia: Royal Soc. West. Australia Jour., v. 41, p. 13–16.

JOHNSTONE, D., and PLAYFORD, P. E., 1955, Geology of the Shark Bay–Murchison River area, Carnarvon Basin: West. Australian Petroleum Pty Ltd report (unpublished).

JOHNSTONE, M. H., 1955, Giralia 1 well completion report: West. Australian Petroleum Pty Ltd report (unpublished).

JOHNSTONE, M. H., 1979, A case history of Rough Range: APEA Jour., v. 19, pt 1, p. 1–6.

JOHNSTONE, M. H., and PUDOVSKIS, V., 1955, Warroora No. 1 well completion report: West. Australian Petroleum Pty. Ltd. report (unpublished).

JOHNSTONE, M. H., BURDETT, J. W., SMITH, D. N., and PEARSON, G. R., 1963, Marilla No. 1 and Minderoo No. 1 stratigraphic bores, Carnarvon Basin, Western Australia: West. Australian Petroleum Pty. Ltd. report (unpublished).

JOHNSTONE, M. H., JONES, D. K., PEARSON, G. R., SMITH, D. N., and THOMAS, B. M., 1976, The Phanerozoic of the Perth and Carnarvon Basins, Western Australia: Int. Geol. Congress, 25th, Sydney, Excursion Guide 39C.

JONES, D. K., 1967, Onslow No. 1 well, Western Australia, well completion report: West. Australian Petroleum Pty. Ltd. report (unpublished).

KAYE, P., EDMOND, G. M., and CHALLINOR, A., 1972, The Rankin Trend, Northwest Shelf, Western Australia: APEA Jour., v. 12, p. 3–8.

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 Jour. Australian Geology Geophysics., v. 2, p. 177–208.

KEMPIN, E., and FUJIOKA, N., 1973, Tamala No. 1 well, Western Australia: Oceania Petroleum Pty. Ltd. report (unpublished).

KENDALL, A. C., 1979a, Continental and supratidal (sabkha) evaporites; *in* Facies Models, *edited by* R. G. WALKER: Geoscience Canada Reprint Series 1.

KENDALL, A. C., 1979b, Subaqueous evaporites *in* Facies Models, *edited by* R. G. WALKER: Geoscience Canada Reprint Series 1.

KENDRICK, G. W., 1978, New species of fossil non-marine molluscs from Western Australia and evidence of later Quaternary climatic change in the Shark Bay district: Royal Soc. West. Australia Jour., v. 60, pt 2, p. 49–60.

KINGSTON, D. R., DISHROON, C. P., and WILLIAMS, P. A., 1983, Global basin classification system: Amer. Assoc. Petroleum Geol. Bull. v. 67, no. 12, p. 2175–2193.

KOLUZS, D., 1972, Hartogen Moogooree No. 1 and 2, and Hartogen Bidgemia No. 1 well completion reports: Hartogen Exploration Pty. Ltd. report (unpublished).

KONECKI, M. C., DICKINS, J. M., and QUINLAN, T., 1958, The geology of the coastal area between the lower Gascoyne and Murchison River areas, Western Australia: Australia BMR Rept. 37.

KOPSEN, E., and McGANN, G., 1985, A review of the hydrocarbon habitat of the eastern and central Barrow-Dampier Sub-basin, Western Australia: APEA Jour., v. 25, pt 1, p. 154–176.

KREISA, R. D., 1981, Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of southwestern Virginia: Jour. Sedimentary Petrology, v. 51, pt 3, p. 823–848.

KRIEWALDT, M. J. B., 1964, Dampier and Barrow Island, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

KUKLA, G. J., 1977, Pleistocene land-sea correlations; 1. Europe: Earth Science Reviews, v. 13, p. 307–374.

KYAW NYEIN, R., MacLEAN, L., and WARRIS, B. J., 1977, Occurrence, prediction and control of geopressures on the Northwest Shelf of Australia: APEA Jour., v. 17, pt 1, p. 64–72.

LARSON, R. L., 1977, Early Cretaceous breakup of Gondwanaland off Western Australia: Geology, v. 5, p. 57–60.

LAVARING, I. H., 1979, Palaeoecological and palaeogeographic implications of *Rhipidomella michelini?* (Leveille) in the Carboniferous of the Carnarvon Basin: West. Australia Geol. Survey Ann. Rept. 1978, p. 89–92.

LAVARING, I. H., 1984, Wave and river dominated delta systems of the Early Permian Wooramel Group, Carnarvon Basin: Seventh Australian Geological Convention, Sydney, 1984, Geol. Soc. Australia, Abstracts 12.

LEHMANN, P. R., 1967, Kennedy Range No. 1 well completion report: West. Australian Petroleum Pty. Ltd. report (unpublished).

LEHMANN, P. R., 1984, The stratigraphy, palaeogeography and petroleum potential of the Lower to lower Upper Devonian sequence in the Canning Basin, *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Proceedings of Geol. Soc. Aust./Petrol. Expl. Soc. Aust. Symposium, Perth, 1984, p. 253–275.

Le MAITRE, R. W., 1975, Volcanic rocks from Edel No. 1 petroleum exploration well, offshore Carnarvon Basin, Western Australia: Australia Geol. Soc. Jour. v. 22, p. 167–174.

LINDSAY, J. F., 1970, Depositional Environment of Paleozoic Glacial Rocks in the Central Transantarctic Mountains: Geol. Soc. Amer. Bull. v. 81, p. 1149–1172.

LOGAN, B. W., 1968, Western Australia: *in* Quaternary shorelines research in Australia and New Zealand, *edited by* E. D. GILL: Australian Jour. Science, v. 31, p. 110.

LOGAN, B. W., 1974, Inventory of diagenesis in Holocene–Recent carbonate sediments, Shark Bay, Western Australia: Amer. Assoc. Petroleum Geol. Mem. 22, p. 195–249.

LOGAN, B. W., BROWN, R. G., and QUILTY, P. G., 1976, Carbonate sediments of the west coast of Western Australia: 25th Int. Geological Congress Excursion Guide 37A.

LOGAN, B. W., DAVIES, G. R., READ, J. F., and CEBULSKI, D. E., 1970, Carbonate sedimentation and environments, Shark Bay, Western Australia: Amer. Assoc. Petroleum Geol. Mem. 13, 223 p.

LOGAN, B. W., READ, J. F., and DAVIES, G. R., 1970, History of Carbonate Sedimentation, Quaternary epoch, Shark Bay, Western Australia: Amer. Assoc. Petroleum Geol. Mem. 13, p. 38–84.

LOGAN, B. W., READ, J. F., HAGAN, G. M., HOFFMAN, P., BROWN, R. G., WOODS, P. J., and GEBELEIN, C. D., 1974, Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia: Amer. Assoc. Petroleum Geol. Mem. 22, p. 140–194.

LOUTIT, T. S., and KENNETT, J. P., 1981, New Zealand and Australian Cenozoic sedimentary cycles and global sea level changes: Amer. Assoc. Petroleum Geol., v. 65, p. 1586–1601.

LOW, G. H., 1975, Proterozoic rocks on or adjoining the Yilgarn Block: West. Australia Geol. Survey Mem. 2, p. 71–81.

LOWRY, D. C., 1977, Seismic foresetting and delta-slope sandstones of the Barrow Group: West Australian Petroleum Pty Ltd report (unpublished).

LOWRY, D. C., 1978, Barrow Group correlations and gross sand deposition: West Australian Petroleum Pty Ltd report (unpublished).

LUDBROOK, N. H., 1967, Correlation of the Tertiary rocks of the Australasian region, *in* Tertiary correlations and climatic changes in the Pacific, *edited by* K. HATAI: Sendai, Japan, Sasaki.

LUDBROOK, N. H., 1978, Australia; *in* The Phanerozoic geology of the world II; the Mesozoic, A, *edited by* M. MOULLADE, and A. E. M. NAIRN: Elsevier, Amsterdam, p. 209–249.

McBRIDE, E. F., and FOLK, R. L., 1979, Features and origin of Italian Jurassic radiolarites deposited on a continental crust: Jour. Sedimentary Petrology, v. 49, no. 3, p. 837–868.

McCUBBIN, D. G., 1982, Barrier-island and strand plain facies: *in* Sandstone Depositional Environments *edited by* P. A. SCHOLLE and D. SPEARING: Amer. Assoc. Petroleum Geol. Mem. 31, p. 247–279.

McEWEN, R. C., 1964, Results of the 1964 testing programme at Cape Range, Western Australia: The Broken Hill Proprietary Co. Ltd. (unpublished).

McGANN, G. J., 1974, The petrology of the Wooramel Group (Lower Permian) in the Lyons River area, Carnarvon Basin, Western Australia: Royal Soc. West. Australia Jour., v. 57, pt 2, p. 33–37.

McGANN, G. J., 1976, The environment of deposition of the Wooramel Group (Lower Permian), Lyons River area, Carnarvon Basin, Western Australia: Royal Soc. West. Australia Jour., v. 59, pt 2, p. 47–54.

McGOWRAN, B., 1968, Late Cretaceous and early Tertiary correlations in the Indo-Pacific region: Geol. Soc. India Mem. 2, p. 335–360.

McGOWRAN, B., 1977, Maastrichtian to Eocene foraminiferal assemblages in the northern and eastern Indian Ocean region: correlations and historical patterns, *in* Indian Ocean geology and biostratigraphy; studies following Deep-Sea Drilling logs 22–29, *edited by* J. R. HEIRTZLER and others: American Geophysical Union, Washington D. C., p. 417–458.

McGOWRAN, B., 1978, Early Tertiary foraminiferal biostratigraphy in southern Australia: a progress report: Australia BMR Bull. 192, p. 83–95.

MacLEOD, W. N., 1966, The geology and iron deposits of the Hamersley Range area, Western Australia: West. Australia Geol. Survey Bull. 117.

McNAMARA, K. J., 1983, The earliest *Tegulornynchia* (Brachiopoda: Rhynchonellida) and its evolutionary significance: Jour. Palaeontology, v. 57, no. 3, p. 461–473.

McNAMARA, K. J., and PHILIP, G. M., 1980, Australian Tertiary shizosterid echinoids: Alcheringa, v. 4, p. 47–65.

McNAMARA, K. J., and SCOTT, J. K., 1983, A new species of *Banksia* (Proteaceae) from the Eocene Merlinleigh Sandstone of the Kennedy Range, Western Australia: Alcheringa, v. 7, p. 185–193.

McTAVISH, R. A., 1964, Wicherina No. 1 well completion report: West. Australian Petroleum Pty Ltd, Petroleum Search Subsidy Act report (unpublished).

McTAVISH R. A., 1965, Barrow No. 1 well completion report: West. Australian Petroleum Pty. Ltd. report (unpublished).

McWHAE, J. R. H., 1958, Hydrodynamic and salinity studies of the chief aquifers of the Carnarvon Basin: West. Australian Petroleum Pty. Ltd. report (unpublished).

McWHAE, J. R. H., PLAYFORD, P . E., LINDNER, A. W., GLENISTER, B. F., and BALME, B. E., 1958, The stratigraphy of Western Australia: Geol. Soc. Australian Jour., v. 4, pt 2, p. 162.

MacKAY, N. J., 1963, An assessment of the underground water resources of Western Australia: West. Australia Geol. Survey Ann. Rept. 1962, p. 8–13.

MAITLAND, A. G., 1912, Relics of Permo-Carboniferous ice age in Western Australia: Nat. Hist. Soc. West. Australia Jour., v. 4, p. 12–29.

MAITLAND, A. G., 1913, The artesian water resources of Western Australia: Interstate Conference on Artesian Water, Sydney, 1912, Report of Proceedings, Appendix M and N, p. 115–158.

MANN, A. W., and HORWITZ, R. C., 1979, Groundwater calcrete deposits in Australia: some observations from Western Australia: Geol. Soc. Australia Jour., v. 26, p. 293–304.

MARTINSON, N. W., McDONALD, D. R., and KAYE, P., 1973, Exploration on continental shelf of Northwest Australia: Amer. Assoc. Petroleum Geol. Bull., v. 57, pt 6, p. 972–989.

MEATH, J. R., 1972, Cunaloo no. 1 well completion report: West. Australian Petroleum Pty Ltd report (unpublished).

MEATH, J. R., and BIRD, K. J., 1976, The geology of the West Tryal Rocks gas field: APEA Jour., v. 16, pt 1, p. 157–163.

MEATH, J. R., and WRIGHT, J. C., 1974, Hilda no. 1 and Hilda no. 1A well completion report: West. Australian Petroeum Pty Ltd report (unpublished).

MEGALLAA, M. N., 1980, A geophysical study of the Central–Southern Carnarvon Basin: West. Australia Geol. Survey Record 1979/10.

MERCER, C. R., 1967, Completion report BMR 8, Mount Madeline and 9, Daurie Creek, Byro Basin, Western Australia: Australia BMR Rept. 108.

MIALL, A. D., 1977, A review of the braided river depositional environment: Earth Science Reviews, v. 13, p. 1–62.

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. Petroleum Geologists Mem. 5, p. 597–604.

MICHAL, S. S., and GROVES, D. I., 1977, The origin of the Northampton hydrothermal lead-zinc deposits, *in* Recent geological research relating low-temperature aqueous geochemistry to weathering, ore genesis and exploration, *edited by* J. E. GLOVER and D. I. GROVES: West. Australian Univ. Geology Dept. and Extension Service, Pub. no. 1.

MITCHELL, A. H. G., and READING, H. G., Sedimentation and tectonics, *in* Sedimentary environments and facies, *edited by* H. G. READING: Blackwell, London, p. 439–476.

MOLLAN, R. G., CRAIG, R. W., and LOFTING, M. J. W., 1969, Geological framework of the continental shelf off northwestern Australia: APEA Jour., v. 9, pt 2, p. 49–59.

MOORE, P. S., and HOCKING, R. M., 1983, Significance of hummocky cross-stratification in the Permian of the Carnarvon Basin, Western Australia: Jour. Geol. Soc. Australia, v. 30, p. 323–331.

MOORE, P. S., DENMAN, P. D., and HOCKING, R. M., 1980, Sedimentology of the Byro Group (Lower Permian), Carnarvon Basin, Western Australia: West. Australia Geol. Survey Ann. Rept 1979, p. 55–64.

MOORE, P. S., HOCKING, R. M., and DENMAN, P. D., 1980, Sedimentology of the Kennedy Group (Permian), Carnarvon Basin, Western Australia: West. Australia Geol. Survey Ann. Rept 1979, p. 65–72.

MOORS, H. T., 1980, A formation temperature study of the Carnarvon Basin: West. Australia Geol. Survey Ann. Rept 1979, p. 45–51.

MOORS, H. T., 1981a, An alluvial fan–fluvial plain depositional model for the Devonian Willaraddie Formation and Munabia Sandstone of the Carnarvon Basin, Western Australia: West. Australia Geol. Survey Ann. Rept 1980, p. 62–67.

MOORS, H. T., 1981b, A geological bibliography of the Carnarvon Basin to 1980: West. Australia Geol. Survey Record 1981/12.

MUTTI, E., and RICCI LUCCHI, F., 1974, La significance de certaines unites sequentielles dans la series a turbidites: Geol. Soc. France Bull., v. 16, p. 577–582.

NICOLL, R. S., 1979, A Late Devonian age for the Munabia Sandstone, Carnarvon Basin, W.A.: Australia BMR Professional Opinion Geol. 79:034 (unpublished).

NORTH BROKEN HILL LTD, 1981, Temporary reserves 8057H–8076H, Coolcalalaya Sub-basin, via Geraldton: Report for Quarter ended 13th August, 1981 (unpublished).

NORTH BROKEN HILL LTD, 1982, Temporary reserves 8057H–8076H, Coolcalalaya Sub-basin, via Geraldton: Report for Quarter ended 13th February, 1982: (unpublished).

NORTHCOTE, K. H., (*ed.*), 1967, Atlas of Australian soils, Explanatory data for Sheets 5 (Perth–Albany–Esperance area) and 6 (Meckatharra–Hamersley Range area): CSIRO, Melbourne Univ. Press, Melbourne.

OCEAN VENTURES PTY LTD, 1972, Edel No. 1 well completion report (unpublished).

O'NEILL, D. C. 1981, Temporary reserves 7776H–7780H (Yaringa 1:250 000 Sheet Area), Final Report No. W/81/1: Jacia Mine Management and Consulting Services report (unpublished).

ÖPIK, A. A., 1959, Tumblagooda Sandstone trails and their age: Australia BMR Rept 38, p. 3–20.

OSBORNE, D. G., 1972, East Marrilla No. 1 well completion report: West Australian Petroleum Pty Ltd report (unpublished).

PARRISH, J. T. and CURTIS, R. L., 1982, Atmospheric circulation, upwelling and organic-rich rocks in the Mesozoic and Cainozoic eras: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 40, p. 31–66.

PARRISH, J. T., ZIEGLER, A. M. and SCOTESE, C. R., 1982, Rainfall patterns and the distribution of coal and evaporites in the Mesozoic and Cainozoic: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 40, p. 67–102.

PARRY, J. C., 1967, The Barrow Island oilfield: APEA Jour., v. 7, p. 130–133.

PARRY, J. C., 1968, The post Triassic stratigraphy of the northern Carnarvon Basin including the wireline log definition of subsurface units: West Australian Petroleum Pty Ltd report (unpublished).

PASSMORE, J. R., 1968, Lower Gascoyne River, possible flow losses downstream from Kennedy Range dam-site. West Australia Geol. Survey Record 1968/11.

PEARSON, G. R., 1964, Quail no. 1 well completion report: West Australian Petroleum Pty Ltd report (unpublished).

PENDERY, E. C., CAMPBELL, M. D., FARMER, R. T. and McDANIEL, K. W., 1969, Hamelin Pool no. 2 well Completion Report: Magellan Petroleum Pty Ltd report (unpublished).

PERCIVAL, I. G., and COONEY, P. M., 1985, Petroleum geology of the Merlinleigh Sub-basin, Western Australia: APEA Jour., v. 25, pt 1, p. 190–203.

PERRY, W. J., 1965, Completion report, stratigraphic and structural bores BMR 6 and 7, Muderong, Western Australia: Australia BMR Rept 81.

PERRY, W. J., and DICKINS, J. M., 1960, Geology of the Badgeradda area, Western Australia: Australia BMR Rept 46.

PETTIJOHN, F. J., POTTER, P. E., and SIEVER, R., 1973, Sand and sandstone: Springer-Verlag, New York, 618p.

PHILIP, G. M., 1969, Silurian conodonts from the Dirk Hartog Formation, Western Australia: Royal Soc. Victoria Proc., v. 82, p. 287–297.

PHILP, R. P., and GILBERT, T. D., 1980, Application of computerized gas chromatography–mass spectrometry to oil exploration in Australia: APEA Jour., v. 20, pt 1, p. 221–228.

PHILP, R. P., GILBERT, T. D., and FRIEDERICH, J., 1982, Geochemical correlation of Australian crude oils: APEA Jour., v. 22, pt 1, p. 188–199.

PLAYFORD, G., 1981, Late Devonian acritarchs from the Gneudna Formation in the Western Carnarvon Basin, Western Australia: Geobios 14, p. 145–171.

PLAYFORD, G., 1983, The Devonian miospore genus *Geminospora* Balme 1962: a reappraisal based upon topotypic *G. lemurata* (type species): Mem. Assoc. Australasian Palaeontologists, v. 1, p. 311–325.

PLAYFORD, G., and DRING, R. S., 1981, Late Devonian acritarchs from the Carnarvon Basin, Western Australia: Special papers in palaeontology, no. 27, Palaeontological Association, London.

PLAYFORD, P. E., 1980, Environmental controls on the morphology of modern stromatolites at Hamelin Pool, Western Australia: West. Australia Geol. Survey Ann. Rept 1979, p. 73-77.

PLAYFORD, P. E., and CHASE, R. E., 1955, Carnarvon Basin, water bores: West. Australian Petroleum Pty. Ltd. report (unpublished).

PLAYFORD, P. E. and COCKBAIN, A. E., 1976, Modern algal stromatolites at Hamelin Pool, a hypersaline barred basin in Shark Bay, Western Australia, *in* Developments in sedimentology 20, Stromatolites, *edited by* M. R. WALTER: Elsevier, Amsterdam, p. 389–411.

PLAYFORD, P. E., COCKBAIN, A. E., and LOW, G. H., 1976, The geology of the Perth Basin: West Australia Geol. Survey Bull. 124.

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. 223–445.

PLAYFORD, P. E., HORWITZ, R. C., PEERS, R., and BAXTER, J. L. 1970, Geraldton, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

PORRENGA, D. H., 1967, Glauconite and chamosite as depth indicators in the marine environment: Marine Geology v. 5, p. 495–502.

POWELL, D. E., 1976A, Dampier Sub-basin, Carnarvon Basin: *in* Economic Geology of Australia and Papua New Guinea — Petroleum, *edited by* R. B. LESLIE, H. J. EVANS and C. L. KNIGHT: Australasian Inst. Mining. Metall. Mon. 7, p. 155–165.

POWELL, D. E., 1976b, The geological evolution of the continental margin off northwest Australia: APEA. Jour., v. 16, pt 1, p. 13–23.

POWELL, D. E., 1982, The northwest Australian continental margin: Phil. Trans. Royal Soc. London, v. 305, p. 45–62.

POWELL, T. G., and McKIRDY, D. M., 1972, The geochemical characterization of Australian crude oils: APEA Jour., v. 12, p. 125–131.

POWELL, W. D., BROAD, D. S., and WILLIAMS, A. J., 1987, Structure, stratigraphy and hydrocarbon potential of the Jurassic and Neocomian of the offshore Carnarvon Basin: West Australian Petroleum Pty Ltd report (unpublished).

PUDOVSKIS, V., 1962, Wandagee no. 1 well completion report West Australian Petroleum Pty Ltd report (unpublished).

QUILTY, P. G., 1974, Tertiary stratigraphy of Western Australia: Geol. Soc. Australia Jour., v. 21, p. 301–318.

QUILTY, P. G., 1977, Cenozoic sedimentation cycles in Western Australia: Geology, v. 5, p. 336–340.

QUILTY, P. G., 1980, Sedimentation cycles in the Cretaceous and Cainozoic of Western Australia: Tectonophysics, v. 63 p. 349–366.

RADKE, B., and NICOLL, R. S., 1981, Evidence for former evaporites in the Carboniferous Moogooree Limestone, Carnarvon Basin, Western Australia: BMR Jour. Australian Geology Geophysics, v. 6, pt 1, p. 106–108.

RAGGATT, H. G., 1936, Geology of the North-West Basin, Western Australia, with particular reference to the stratigraphy of the Permo-Carboniferous: Royal Soc. New South Wales Jour., v. 70, p. 100–174.

RAGGATT, H. G., 1964, Progress in the search for petroleum: Australian Oil and gas Jour., v. 11, no. 1.

READ, J. F., ALCOCK, P. J., and HOSEMAN, P., 1973, Harris Sandstone–Yindagindy Formation relationships and possible position of Permo-Carboniferous boundary, Carnarvon Basin, Western Australia: Royal Soc. West. Australia Jour., v. 56, p. 80–85.

READING, H. G., (*ed.*), 1978, Sedimentary environments and facies: Blackwell Scientific Publ., London.

RENFRO, A. R., 1974, Genesis of evaporite–associated stratiform metalliferous deposits — a sabkha process: Econ. Geol., v. 69, p. 33–45.

REVELLE, R., and FAIRBRIDGE, R., 1957, Carbonates and Carbon Dioxide, *in* Treatise on marine ecology and paleoecology, v. 1, Ecology, *edited by* J. W. HEDPETH; Geol. Soc. Amer. Mem. 67.

RICHARDSON, J. A., 1981, E.P. 169 Carnarvon Basin, W.A., Annual report for year ending 6 June 1981 (revised): Layton and Associates Pty Ltd report (unpublished.).

RIDE, W. D. G, APPLEYARD, R. T., BALME, B. E., and MORGAN, J. F., 1974, Report on the conservation through reserves committee: Perth, The Environmental Protection Authority, West. Australia.

RIGBY, J. K., 1983, A first report of Cretaceous sponges from the Carnarvon Basin in Western Australia: Jour. Paleont., v. 57, no. 4, p. 766–772.

ROBERTSON, C. S., CRONK, D. K., LOCKWOOD, K. L., and MAYNE, S. J., 1978, A review of petroleum exploration and prospects in the Carnarvon Basin: Australia BMR Record 1978/47, p. 1–139.

ROBERTSON RESEARCH INTERNATIONAL LTD, 1979, Petroleum Geochemistry of the Australian Northwest Shelf: report, 3 volumes, (unpublished).

ROSS, C. A., and ROSS, J. R. P., 1979, Permian: Treatise on invertebrate paleontology: Part A, Introduction: Geol. Soc. Amer, and Univ. Kansas Press, p. A291–350.

RUNNEGAR, B. N., 1969, The Permian faunal succession in eastern Australia: Geol. Soc. Australia Spec. Pub. 2, p. 73–98.

RUSSELL, R. T., 1965, Examination of well samples for sedimentary phosphate, Carnarvon Basin, Western Australia: Mines Exploration Pty Ltd report (unpublished).

SAMANTHA EXPLORATION N.L., OTTER EXPLORATION N.L., and ALLSTATE EXPLORATION N.L., 1981, Temporary reserves 7846–8H and 8418–9H, Muggon Station, Byro area, Western Australia: final report (unpublished).

SCHOOLE, P. A., and ARTHUR, M. A., 1980, Carbon isotope fluctuations in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tool: Amer. Association Petroleum Geol. Bull., v. 64, p. 67–87.

SCOTESE, C., BAMBACH, R. K., BARTON, C., van der VOO, R., and ZIEGLER, A., 1979, Paleozoic base maps: Jour. Geology, v. 87, p. 217–277.

SEDDON, G., 1969, Conodont and fish remains from the Gneudna Formation, Carnarvon Basin, Western Australia: Royal Soc. West. Australia Jour. v. 52, p. 21–30.

SEILACHER, A., 1978, Use of trace fossil assemblages for recognizing depositional environments, *in* Trace fossil concepts, *edited by* P. B. BASAN: Soc. Econ. Paleontologists Mineralogists Short Course 5, p. 167–181.

SINGLETON, F. A., 1941, The Tertiary geology of Australia: Royal Soc. Victoria Proc., v. 53, p. 1–125.

SKWARKO, S. K., 1966, Cretaceous stratigraphy and palaeontology of the Northern Territory: Australia BMR Bull. 73.

SKWARKO, S. K., and KUMMEL, B., 1974, Marine Triassic molluscs of Australia and Papua New Guinea: Australia BMR Bull. 150, p. 111–128.

SMITH, A. G., HURLEY, A. M., and BRIDEN, J. C., 1981, Phanerozoic Palaeocontinental Maps: Cambridge University Press, Cambridge, 102p.

SUMMERFIELD, M. A., 1983, Silcrete as a palaeoclimate indicator: evidence from Southern Africa: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 41, p. 65–79.

SUMMERS, K. W. A., 1966, Temporary reserves 3170H and 3169H (Phosphate), Gascoyne Junction and Kennedy Range: Electrolytic Zinc Company of Australasia Ltd report (unpublished).

TAIT, A. M., 1985, A depositional model for the Dupuy Member and the Barrow Group in the Barrow Sub-basin, Western Australia: APEA Jour., v. 25, pt 1, p. 282–290.

TEICHERT, C., 1941, Upper Palaeozoic of Western Australia; correlation and palaeogeography: Amer. Assoc. Petroleum Geol. Bull., v. 25, p. 371–415.

TEICHERT, C., 1949, Discovery of Devonian and Carboniferous rocks in the North-West Basin, Western Australia: Australian Jour. Sc., v. 12, p. 62–65.

TEICHERT, C., 1950, Some recent additions to the stratigraphy of Western Australia: Amer. Assoc. Petroleum Geol. Bull., v. 34, p. 1787–1794.

TEICHERT, C., 1957, Notes on the geology of the Carnarvon (Northwest) Basin, Western Australia: Royal Soc. West. Australia Jour., v. 40, p. 65–72.

THE BROKEN HILL PROPRIETARY COMPANY LIMITED, 1976a, Temporary reserve 5951H, Merlinleigh Basin, Western Australia: report (unpublished).

THE BROKEN HILL PROPRIETARY COMPANY LIMITED, 1976b, Temporary reserve 5952H, Merlinleigh Basin, Gascoyne Goldfields, Western Australia: final report (unpublished).

THE BROKEN HILL PROPRIETARY COMPANY LIMITED, 1976c, Temporary reserve 5953H, Merlinleigh Basin, Gascoyne Goldfields, Western Australia: final report (unpublished).

THOMAS, B. M., 1974, Carnarvon Basin: the Neocomian and Tithonian of Barrow Island — a review: West. Australian Petroleum Pty Ltd report (unpublished).

THOMAS, B. M., 1978, Robe River — an onshore shallow oil accumulation: APEA Jour., v. 18, pt 1, p. 3–12.

THOMAS, B. M., and SMITH, D. N., 1974, A summary of the Petroleum Geology of the Carnarvon Basin: APEA Jour., v. 14, pt. 1, p. 64–76.

THOMAS, B. M., and SMITH, D. N., 1976, Carnarvon Basin, *in* Economic geology of Australia and Papua New Guinea Petroleum, *edited by* R. B. LESLIE, H. J. EVANS, and C. L. KNIGHT: Australasian Inst. Mining Metall. Mon. 7, p. 126–155.

THOMAS, G. A., 1971, Carboniferous and Early Permian brachiopods from Western Australia and Northern Australia: Australia BMR Bull. 56, p. 1–267.

THOMAS, J. S., NESTROLD, E. O., and CROSTELLA, A., 1978, Australia's Northwest Shelf: Gas is the current attraction: World Oil, v. 187, pt 5, p. 141–156.

TOWNER, R. R., and GIBSON, D. L., 1983, Geology of the Onshore Canning Basin, Western Australia: Australia BMR Bull. 215.

VAIL, P. R., MITCHUM, R. M. jnr, and THOMPSON, S. III, 1977, Global cycles of relative changes of sea level: Amer. Assoc. Petroleum Geol. Mem. 26, p. 83–97.

VALSARDIEU, C. A., HARROP, D. W., and MORABITO, J., 1981, Discovery of uranium mineralization in the Manyingee Channel, Onslow Region of Western Australia: Australasian Inst. Mining Metall. Proc., no. 279, p. 5–17.

van de GRAAFF, W. J. E., 1981, Early Permian Lyons Formation, Carnarvon Basin, Western Australia, *in* Earth's pre-Pleistocene glacial record, *edited by* M. J. HAMBREY and W. B. HARLAND, Cambridge University Press, Cambridge, p. 453–458.

van de GRAAFF, W. J. E., CROWE, R. W. A., BUNTING, J. A., and JACKSON, M. J., 1977, Relict Early Cainozoic drainages in arid Western Australia: Z. geomorph. N. F., v. 21, p. 379–400.

van de GRAAFF, W. J. E., DENMAN, P. D., and HOCKING, R. M., 1976, Emerged Pleistocene marine terraces on Cape Range, Western Australia: West. Australia Geol. Survey Ann. Rept. 1975, p. 62–70.

van de GRAAFF, W. J. E., DENMAN, P. D., and HOCKING, R. M., 1982, Onslow, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

van de GRAAFF, W. J. E., DENMAN, P. D., and HOCKING, R. M., and BAXTER, J. L., 1980, Yanrey–Ningaloo, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

van de GRAAFF, W. J. E., HOCKING, R. M., and BUTCHER, B. P., 1983, Yaringa, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

van de GRAAFF, W. J. E., HOCKING, R. M., and DENMAN, P. D., 1977, Revised stratigraphic nomenclature and interpretations in the east-central Carnarvon Basin, W.A.: West. Australia Geol. Survey Ann. Rept 1976, p. 37–39.

VEEH, H. H., SCHWEBEL, D., van de GRAAFF, W. J. E., and DENMAN, P. D., 1979, Uranium-series ages of coralline terrace deposits in Western Australia: Geol. Soc. Australia Jour., v. 26, p. 285–292.

VEENSTRA, E., 1985, Rift and drift in the Dampier Subbasin, a seismic and structural interpretation: APEA Jour., v. 25, pt 1, p. 177–189.

VEEVERS, J. J., 1971, Phanerozoic history of Western Australia related to continental drift: Geol. Soc. Australia Jour., v. 18, p. 87–96.

VEEVERS, J. J., 1972, Evolution of the Perth and Carnarvon Basins: APEA Journal, v. 12, pt. 2, p. 52–54.

VEEVERS, J. J., 1973, Stratigraphy and structure of the continental margin between North West Cape and Seringapatam Reef, northwest Australia: Australia BMR Bull. 139, p. 79–102.

VEEVERS, J. J., 1976, Early Phanerozoic events on and alongside the Australasian-Antarctic platform: Geol. Soc. Australia Jour., v. 23, p. 183–206.

VEEVERS, J. J. (*ed*), 1984, Phanerozoic earth history of Australia: Oxford University Press, Oxford, p. 418.

VEEVERS, J. J., and COTTERILL, D., 1978, Western margin of Australia: evolution of a rifted arch system: Geol. Soc. Amer. Bull., v. 89, p. 337–355.

VEEVERS, J. J., and JOHNSTONE, M. H., 1974, Comparative stratigraphy and structure of the Western Australian margin and the adjacent deep ocean floor: Deep sea drilling Project Initial Report 27, p. 571–586.

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.

VENTRISS, H. B., 1980, Gascoyne River groundwater scheme yield study. West. Australia Public Works Dept. Water Resources Tech. Paper No. 91.

VENTRISS, H. B., and PARSONS, G. W., 1978a, Groundwater system review, Exmouth: West. Australia Public Works Dept, Water Resources Branch report.

VENTRISS, H. B., and PARSONS, G. W., 1978b, Groundwater system review, Kalbarri: West. Australia Public Works Dept, Water Resources Branch report.

VENTRISS, H. B., and PARSONS, G. W., 1979, Groundwater system review Onslow, June 1979. West. Australia Public Works Dept, Water Resources Branch report.

VENTRISS, H. B. and SMITH, T. A. 1979, Groundwater system review Gascoyne Junction: West. Australia Public Works Dept, Water Resources Branch report.

VOSS, R. G., and McHATTIE, C. M., 1981, Upper Triassic depositional environments, central Exmouth Plateau (Permit WA-84-P), Northwestern Australia: Fifth Australian Geol. Convention, Perth 1981. Geol. Soc. Australia, Abstracts.

WALKER, R. G., 1979a, Shallow marine sands, *in* Facies models, *edited by* R. G. WALKER: Geoscience Canada Reprint Series 1, p. 75-89.

WALKER, R. G., 1979b, Turbidites and associated coarse clastic deposits, *in* Facies models, *edited by* R. G. WALKER: Geoscience Canada Reprint Series 1, p. 91–103.

WALKER, R. G., 1981, Clastic sedimentary facies and depositional models: Short Course notes, Australian Sedimentologists Group and Monash University, October 1981, Geol. Soc. Australia, (unpublished).

WARRISS, B. J., 1973, Plate tectonics and the evolution of the Timor Sea, northwest Australia: APEA Journal, v. 13, p. 13–18.

WATERHOUSE, J. B., 1970, Gondwanan occurrences of the upper Paleozoic brachiopod *Stepanoviella:* Journal Paleonotology, v. 44, p. 37–50.

WELLS, A. T., Evaporites in Australia: Australia BMR Bull. 198.

WHITE, M. E., 1959, Botanical report on a Lepidodendroid log from the Harris Sandstone, Carnarvon Basin, Western Australia: Australia BMR Rept 38, p. 53–54.

WHITE, M. E., and CONDON, M. A., 1959, A species of *lepidodendron* from the basal Lyons Group, Carnarvon Basin, Western Australia: BMR Rept 38, p. 55–64.

WILLCOX, J. B., and EXON, N. E., 1976, The regional geology of the Exmouth Plateau: APEA Jour., v. 16, pt 1, p. 1–11.

WILLIAMS, A. F., and POYNTON, D. J., 1985, The geology and evolution of the South Pepper hydrocarbon accumulation: APEA Jour., v. 25, pt 1, p. 235–247.

WILLIAMS, C. T., 1977, An analysis of the production performance of the Windalia Sand reservoir of the Barrow Island oilfield: APEA Jour., v. 17, pt 1, p. 105–113.

WILLIAMS, I. R., 1965, Notes on a mound spring on Mardie Station, near Cape Preston: West. Australia Geol. Survey Annual Rept 1964, p. 36.

WILLIAMS, I. R., 1968, Yarraloola, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

WILLIAMS, I. R., WALKER, I. W., HOCKING, R. M., and WILLIAMS, S. J., 1983, Byro, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

WILLIAMS, S. J., WILLIAMS, I. R., and HOCKING, R. M., 1983, Glenburgh, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

WILLIAMS, S. J., WILLIAMS, I. R., CHIN, R. J., MUHLING, P. C., and HOCKING, R. M., 1983, Mount Phillips, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

WISEMAN, J. F., 1979, Neocomian eustatic changes—biostratigraphic evidence from the Carnarvon Basin: APEA Jour., v. 19, pt 1, p. 66–73.

WISEMAN, J. F., 1980, Palynostratigraphy near the "Jurassic–Cretaceous boundary" in the Carnarvon Basin, Western Australia: Fourth Int. Palynol. Conf., Lucknow 1976, Proceedings, v. 2, p. 330–349.

WOPFNER, H., 1978, Die Klimaentwicklung des Perms in Sudund Zentralaustralien: Sonderveroff. Geolog. Inst. Univ. Koln, 33, Cologne, p. 259–279.

WOPFNER, H, 1981, Development of Permian intracratonic basins in Australia: Fifth Int. Gondwana Symposium, Wellington, New Zealand, 1980, Proceedings.

WRIGHT, A. J., and WHEATLY, T. J., 1979, Trapping mechanisms and the hydrocarbon potential of the Exmouth Plateau, Western Australia: APEA Jour., v. 19, pt 1, p. 19–29.

WRIGHT, C. A., and APTHORPE, M. C., 1976, Planktonic foraminiferids from the Maastrichtian of the Northwest Shelf, Western Australia: Jour. Foraminiferal Research, v. 6, no. 3, p. 228-240.

WYROLL, K–H., 1979, Late Quaternary climates of Western Australia: evidence and mechanisms: Royal Soc. West. Australia Jour., v. 62, p. 129–142.

YEATES, A. N., GIBSON, D. L., TOWNER, R. R., and CROWE, R. W. A. 1984, Regional geology of the onshore Canning Basin, W. A., *in* The Canning Basin, W.A., *edited by* P. G. PURCELL: Proceedings of Geol. Soc. Aust/Petrol. Expl. Soc. Australia Symposium, Perth, 1984, p. 23–56.

YOUNG, R. J. B., and WRIGHT, J. C., 1978, Mermaid No. 1 well completion report: West. Australian Petroleum Pty. Ltd. report (unpublished).

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CARNARVON BASIN

INDIAN OCEAN

REFERENCE

QUATERNARY

? PLIOCENE – HOLOCENE

Qm Qs Ql Qa Qe

COASTAL

Qm Marine dominated : intertidal and supratidal deposits, minor beach ridge, coastal dune and coastal lake deposits; mostly calcareous, commonly algal bound or coralgal. Includes **BIBRA and DAMPIER LIMESTONES** (Shark Bay area) and marine and shoreline components of **BUNDERA CALCARENITE and EXMOUTH SANDSTONE** (north of Carnarvon)

Qs Eolian dominated : coastal dune and beach ridge deposits, minor supratidal and coastal lake deposits; mostly calcareous sand and calcarenite. Includes **TAMALA and BOSSUT LIMESTONES** and eolian components of **BUNDERA CALCARENITE and EXMOUTH SANDSTONE**

Ql Lacustrine : coastal saline lake and lake-derived deposits; clay, silt, sand and gravel, in part evaporitic

CONTINENTAL

Qa Alluvial dominated : alluvial, diluvial and colluvial deposits ; includes groundwater (valley) calcrete where not clearly exposed; commonly shows some eolian reworking

Qe Eolian dominated : sand plains and dunes; includes residual and reworked areas and some dune-and-playa terrain, excludes calcareous coastal dunes

PLIOCENE – PLEISTOCENE

Czk Czv

Czk Calcareous duricrust (calcrete) : authigenic limestone, in places omitted to clarify underlying geology

Czv Groundwater (valley) calcrete and lacustrine valley-fill deposits **(NADARRA FORMATION)**: mudstone, calcreted mudstone, authigenic limestone and calcreted alluvium

OLIGOCENE – MIOCENE

Czd

Siliceous and ferruginous duricrust : laterite, silcrete, intensely silicified and/or ferruginized bedrock, and **PINDILYA FORMATION**; commonly omitted to clarify underlying geology

TERTIARY

MIOCENE

MIDDLE

Tp Tt Tk Ta

CAPE RANGE GROUP

Tp **PILGRAMUNNA FORMATION, VLAMING and LAMONT SANDSTONES :** quartzose calcarenite, quartz arenite, minor coralgal limestone; marine to littoral (Pilgramunna), eolian (Vlaming) and littoral to fluvial (Lamont)

Tt **TREALLA LIMESTONE :** calcarenite to calcirudite with coralgal limestone, minor calcilutite; high energy shallow-marine. Includes **BULLARA LIMESTONE** in Rough Range

Tk **TULKI LIMESTONE :** foraminiferal calcarenite and algal limestone, partly marly; low to moderate energy shallow-marine

Ta **MANDU CALCARENITE :** foraminiferal calcarenite, calcilutite and marl; low energy marine, shallowing upwards

LOWER

MIDDLE–UPPER EOCENE

Tg Tm Tr

Tg **GIRALIA CALCARENITE :** calcarenite, commonly ferruginized and/or quartzose; moderate to high energy shallow-marine

Tm **MERLINLEIGH SANDSTONE :** quartz arenite and quartz wacke, minor granule conglomerate, sparsely fossiliferous, commonly lateritized; shallow-marine to fluvial

Tr **ROBE PISOLITE :** reworked pisolitic laterite; ? fluvial and residual

PALEOCENE

Tc

CARDABIA CALCARENITE : calcarenite, calcilutite and calciluite with basal greensand, glauconitic in lower part and locally chalky; low to moderate energy marine

CRETACEOUS

UPPER

MAASTRICHTIAN

TURONIAN

LOWER

ALBIAN

APTIAN

NEOCOMIAN

Ks Kt Kg Kw Kb Kn

CARNARVON BASIN

Kt **TOOLONGA CALCILUTITE :** chalky calcilutite, calcilutite and calcarenite, includes **MIRIA FORMATION and KOROJON CALCARENITE** (Giralia Anticline); low to moderate energy marine

Kg **GEARLE SILTSTONE :** bentonitic siltstone and radiolarite, minor bedded and secondary gypsum and barite; low energy marine

Kw **WINDALIA RADIOLARITE :** radiolarian siltstone and claystone, commonly varicoloured and porcellanized in outcrop, locally includes minor **MUDERONG SHALE**; shallow-marine

Kb **BIRDRONG SANDSTONE :** friable quartz sandstone and siltstone, commonly glauconitic, generally includes **MUDERONG SHALE**; shallow-marine shoreface grading to offshore, minor fluvial

Kn **NANUTARRA FORMATION and YARRALOOLA CONGLOMERATE :** sandstone, siltstone and conglomerate; fluvial to tidal, basin-marginal deposits

Kw **BIRDRONG SANDSTONE, MUDERONG SHALE and WINDALIA RADIOLARITE :** undifferentiated sequence, Kennedy Range area. Includes **NANUTARRA FORMATION** in Nanyingee Hill area

JURASSIC AND TRIASSIC

TJs Ps

SOUTHERN CARNARVON BASIN – PERTH BASIN

Ks **BIRDRONG SANDSTONE, WINDALIA RADIOLARITE, ALINGA FORMATION and TOOLONGA CALCILUTITE :** undifferentiated sequence, Kalbarri area

TJs **KOCKATEA SHALE, CHAPMAN and CHAMPION BAY GROUPS :** undifferentiated siliciclastic Perth Basin sediments south of Murchison River

Ps **TUMBLAGOODA SANDSTONE, WITTECARRA SANDSTONE, KOCKATEA SHALE and BIRDRONG SANDSTONE :** sequence in cliff exposure south of Kalbarri

CRETACEOUS, TRIASSIC AND SILURIAN

PERMIAN

UPPER

? ROADIAN

LOWER

ARTINSKIAN

SAKMARIAN

CARBONIFEROUS

STEPHANIAN

TOURNAISIAN

VISEAN

DEVONIAN

FAMENNIAN

FRASNIAN

? DEVONIAN

SILURIAN

PRECAMBRIAN

PKb PK PBu PBm PBl PW P

KENNEDY GROUP : siliciclastic marine shelf sequence

BINTHALYA FORMATION : quartz wacke, siltstone and carbonaceous shale; offshore marine to inner shelf

COOLKILYA and MUNGADAN SANDSTONES : quartz wacke, quartz arenite and siltstone; marine shelf. Includes **BINTHALYA FORMATION** at Wandagee Hill

BYRO GROUP : siliciclastic, storm-dominated marine shelf sequence

Upper : **WANDAGEE FORMATION, NALBIA SANDSTONE and BAKER FORMATION :** siltstone and quartz wacke, bioturbated and fossiliferous; marine, offshore to shoreface

Middle : **BULGADDO SHALE, CUNDLEGO FORMATION** and (Wandagee area) **QUINNANIE SHALE :** shale, siltstone and (in Cundlego) quartz wacke; offshore (Bulgaddo, Quinnanie) and shallow-marine (Cundlego)

Lower : **COYRIE FORMATION and MALLENS SANDSTONE :** siltstone, quartz wacke, minor quartz arenite; offshore (Coyrie) and shallow-marine (Mallens)

WOORAMEL GROUP : siliciclastic fluvial to marine deltaic sequence

CORDALIA SANDSTONE (north of 24°S), **MOOGOOLOO SANDSTONE, BILLIDEE FORMATION** and (South of 25°30'S) **KEOGH FORMATION :** quartz sandstone, siltstone and shale, minor limestone; fluvial, deltaic and marine shelf, deposited in major progradational episode

Pl **CALLYTHARRA FORMATION :** calcareous siltstone and hard calcarenite, very fossiliferous; marine shelf, shoaling in upper part

P LYONS GROUP : tillite, quartz wacke, siltstone and shale, in part calcareous; continental and marine, glacial-dominated. Includes **NANGETTY FORMATION and HOLMWOOD SHALE** in Perth Basin

Cl **MOOGOOREE LIMESTONE, WILLIAMBURY FORMATION and YINDAGINDY FORMATION :** limestone (Moogooree, Yindagindy), conglomerate and quartz sandstone (Williambury, Yindagindy); shallow-marine (Moogooree, Yindagindy) and alluvial fan (Williambury). Includes unnamed clastic sequence south of 26°S

Dm Dq **MUNABIA SANDSTONE and WILLARADDIE FORMATION :** quartz sandstone, siltstone and conglomerate; braided fluvial to littoral (Munabia) and alluvial fan to braided fluvial (Willaraddie)

NANNYARRA SANDSTONE and GNEUDNA FORMATION : siltstone, calcarenite, calciluitite and dolomite (Gneudna), quartz sandstone, minor conglomerate (Nannyarra); shallow-marine and (part of Nannyarra) fluvial

?D Unnamed Palaeozoic sediments : sandstone, siltstone and minor conglomerate, northern Perth Basin; fluvial to shallow marine/littoral. Age uncertain, may be Devonian

St **TUMBLAGOODA SANDSTONE :** sandstone, minor conglomerate and siltstone, commonly red; braided fluvial to tidal "red bed" sequence

Es A–E

Es **Sedimentary Rocks:** Badgeradda, Bangemall, Llaroo, Fortescue, Mount Minnie and Wyloo Groups. Relatively un-metamorphosed Precambrian sediments

A–E **Igneous and Metamorphic Rocks :** Yilgarn, Pilbara and Northampton Blocks, Gascoyne Province

SYMBOLS

Geological boundary

Fault
- Accurate
- Approximate or inferred

Fold
- Syncline, showing plunge
- Anticline, showing plunge

Bedding trend

Lineaments
- Reflecting bedding
- Probable structural origin

Petroleum exploration well
- Drilling in progress
- Oil well
- Gas well
- Oil and gas well
- Suspended oil well
- Suspended gas well
- Suspended oil and gas well
- Suspended gas and condensate well
- Suspended well
- Abandoned well, dry
- Abandoned well, show of oil
- Abandoned well, show of gas
- Abandoned well, show of oil and gas
- Abandoned oil well
- Abandoned gas well
- Abandoned gas and condensate well
- Stratigraphic or structure well (St)

Evaporite exploration well

Artesian or subartesian bore

Position approximate (p.a.)

Highway with national route marker 1

Formed road

Railway, standard gauge

Townsite, population as at 1981 census
- 1 000 – 10 000 ○ DAMPIER
- Under 1 000 ◦ Kalbarri

Locality • Galena

Homestead ■ Karratha

Building ▪

Airfield

Landing ground

Horizontal control; major △

Natural-gas pipeline

Vermin-proof fence

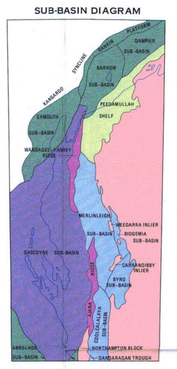
Sand dune

Watercourse; intermittent

Palaeodrainage

Bathymetric contour, depth in metres 100

SUB-BASIN DIAGRAM



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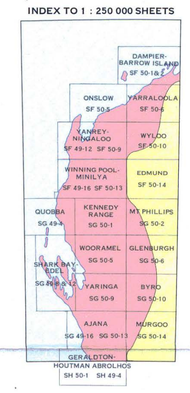
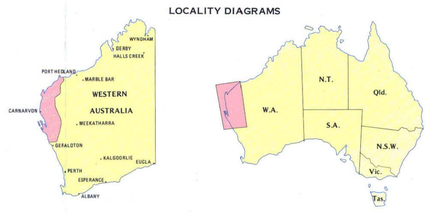


LOCALITY DIAGRAMS



HON. DAVID PARKER, M.L.A.
MINISTER FOR MINERALS AND ENERGY

A. F. TRENDALL, DIRECTOR, GEOLOGICAL SURVEY DIVISION

GEOLOGY OF THE CARNARVON BASIN

SCALE 1 : 1 000 000

20 0 20 40 60 80 100 KILOMETRES

UNIVERSAL TRANSVERSE MERCATOR PROJECTION

ZONE 49 & 50 AUSTRALIAN MAP GRID

Compiled and published by the Geological Survey of Western Australia, 66 Adelaide Terrace, Perth.
Cartography by the Geological Mapping Branch, Surveys and Mapping Division, Department of Mines.
Topographic base from compilations by the Department of Lands and Surveys.

Geology by R.M. Hocking

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CARNARVON BASIN

INDIAN OCEAN

Section extends to 18°52'S 116°5'40"E

REFERENCE

MIDDLE–UPPER JURASSIC

J — NORTHERN CARNARVON BASIN, **DINGO CLAYSTONE** and equivalents : basinal claystone and siltstone with local turbiditic, nearshore, deltaic and fluvial sandstone. Hydrocarbon source and local reservoir

Js — OFFSHORE PERTH BASIN, unassigned sequence : probably equivalent to **COCKLESHELL GULLY FORMATION** and **YARRAGADEE FORMATION**

LOWER JURASSIC

JW — **WOODLEIGH FORMATION** : dark grey to black claystone and siltstone, probably lacustrine

TRIASSIC–LOWER JURASSIC

TRJ — NORTHERN CARNARVON BASIN, **MUNGAROO, BRIGADIER** and **NORTH RANKIN FORMATIONS** : interbedded claystone, siltstone and sandstone, fluvial to shallow marine. Hydrocarbon reservoir

TRJs — PERTH BASIN, **KOCKATEA SHALE, CHAPMAN GROUP, CHAMPION BAY GROUP** : mixed siliciclastic sequence, marine deposits

UPPER PERMIAN–TRIASSIC

PTr — NORTHERN CARNARVON BASIN, **CHINTY FORMATION** and **LOCKER SHALE** : mixed siliciclastic sequence, marine low energy deposits

PTrs — OFFSHORE PERTH BASIN, unassigned sequence

? UPPER PERMIAN

PK — KENNEDY GROUP : interbedded sandstone and siltstone, marine shelf deposit

LOWER PERMIAN

PB — BYRO GROUP : interbedded siltstone, sandstone and shale, marine shelf deposit

PW — WOORAMEL GROUP : sandstone with lesser siltstone and shale. Fluvial to offshore deposits

UPPER CARBONIFEROUS

CP — LYONS GROUP and **CALLYTHARRA FORMATION** : mixed siliciclastic and carbonate sequence, glacially dominated

DEVONIAN–LOWER CARBONIFEROUS

DC — Undifferentiated sequence of probable Devonian to Early Carboniferous age : dark grey to black, generally fine-grained sequence in subsurface

CI — **MOOGOOREE LIMESTONE, WILLIAMBURY FORMATION, YINDAGINDY FORMATION** and **QUAIL FORMATION** : mixed sequence

CIs — Unnamed sequence, Coolcalalaya and Irwin Sub-basins : pale green siltstone

D — **NANNYARRA SANDSTONE, GNEUDNA FORMATION, MUNABIA SANDSTONE, WILLARADDIE FORMATION** : mixed sequence

? DEVONIAN

?D — Unassigned sequence, northern Perth Basin : fine to medium-grained nearshore to fluvial sandstone

SILURIAN

S — KALBARRI GROUP : undifferentiated ; red bed sandstone, carbonate and siltstone

Sd — Carbonate and/or fine-grained facies : includes **DIRK HARTOG** and **SWEENEY MIA FORMATIONS**. Locally evaporitic dolomite, limestone, siltstone and shale, minor sandstone, shallow marine

St — Sandstone facies : includes **TUMBLAGOODA** and **KOPKE SANDSTONES**. Red bed sandstone, minor sandstone, minor siltstone, fluvial to tidal

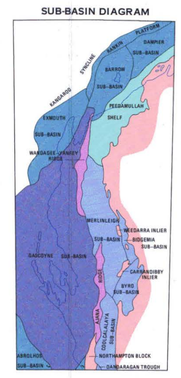
PRECAMBRIAN

A-ℰ — Igneous, metamorphic and sedimentary rocks

SYMBOLS

- Geological boundary
  - Accurate
  - Approximate or inferred
- Fault, inferred from surface geology, airphoto or Landsat lineaments, gravity and/or magnetic data
  - Penetrating up to base Cretaceous
  - Concealed at base Cretaceous
  - Fault name (Kennedy)
- Bedding trend
- Magnetic basement contours (depth in kilometres)
- Petroleum exploration well
  - Drilling in progress
  - Oil well
  - Gas well
  - Oil and gas well
  - Suspended oil well
  - Suspended gas well
  - Suspended oil and gas well
  - Suspended gas and condensate well
  - Suspended well
  - Abandoned well, dry
  - Abandoned well, show of oil
  - Abandoned well, show of gas
  - Abandoned well, show of oil and gas
  - Abandoned oil well
  - Abandoned gas well
  - Abandoned gas and condensate well
  - Stratigraphic or structure well (St)
- Evaporite exploration well
- Mineral company exploration borehole
  - penetrating pre-Cretaceous sequence
  - Kimberlitic intrusive
  - Waterbore penetrating pre-Cretaceous sequence
  - Position approximate (p.a.)
- Highway with national route marker (1)
- Formed road
- Townsite, population as at 1981 census
  - 1 000 – 10 000 (DAMPIER)
  - Under 1 000 (Kalbarri)
- Locality (Galena)

SUB-BASIN DIAGRAM



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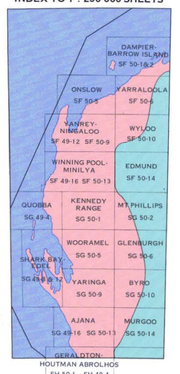

LOCALITY DIAGRAMS

HON. DAVID PARKER, M.L.A.
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INTERPRETED PRE-CRETACEOUS GEOLOGY OF THE CARNARVON BASIN

SCALE 1 : 1 000 000

20 0 20 40 60 80 100 KILOMETRES

UNIVERSAL TRANSVERSE MERCATOR PROJECTION
ZONE 49 & 50 AUSTRALIAN MAP GRID

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Topographic base from compilations by the Department of Lands and Surveys.

Geology by R.M. Hocking and M.H. Johnstone
Magnetic basement contours by R.M. Hocking and M.F. Middleton

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CARNARVON BASIN

DIAGRAMMATIC CROSS-SECTIONS AND PALAEOGEOGRAPHIC RECONSTRUCTIONS

HON. DAVID PARKER, M.L.A.
MINISTER FOR MINERALS AND ENERGY
A. F. TRENDALL, DIRECTOR, GEOLOGICAL SURVEY DIVISION

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Diagrammatic Cross-sections, R.M. Hocking and M.F. Middleton
Palaeogeographic Reconstructions, R.M. Hocking

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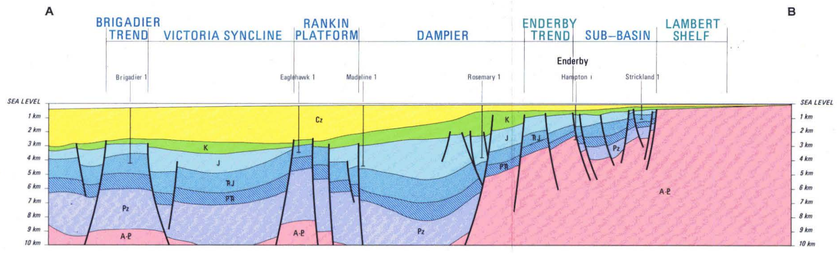
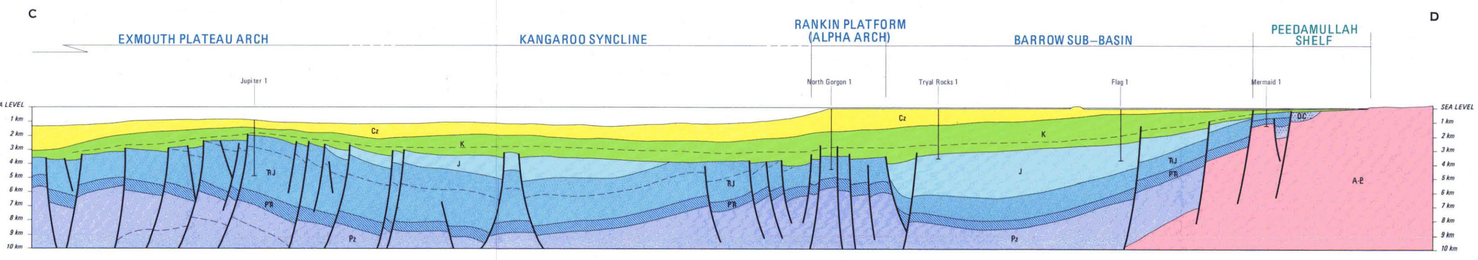
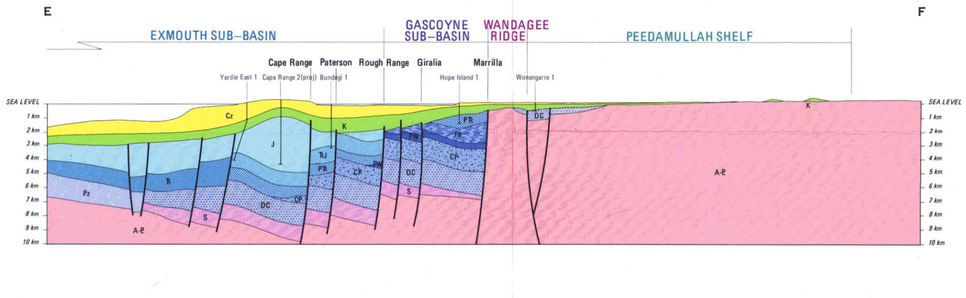
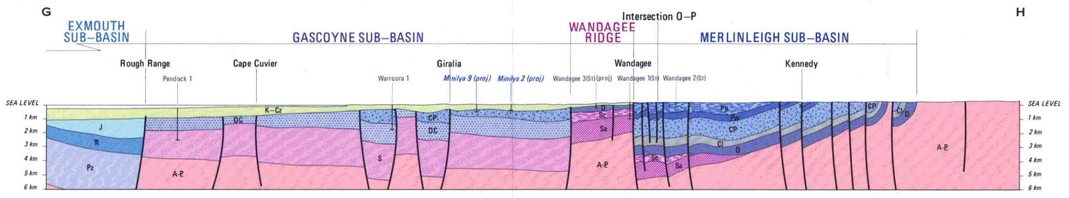
DIAGRAMMATIC CROSS-SECTIONS

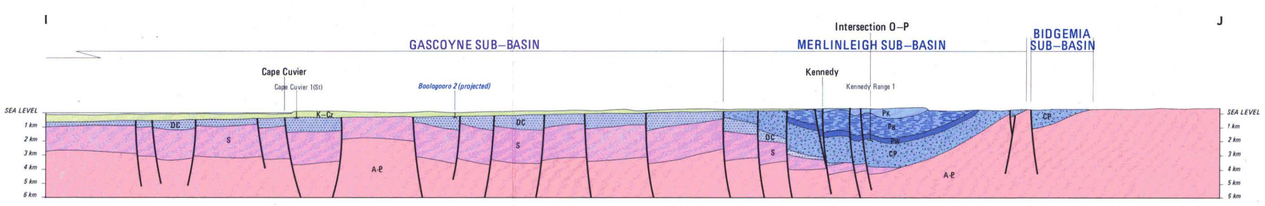
VERTICAL EXAGGERATION x 4

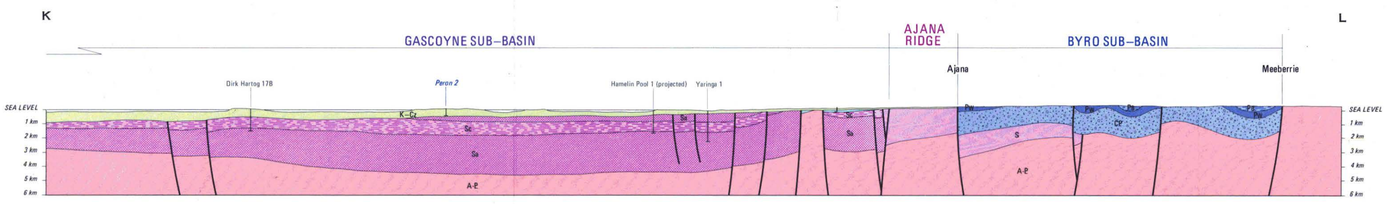


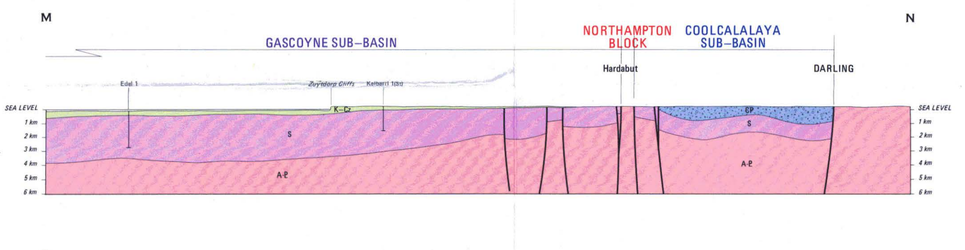


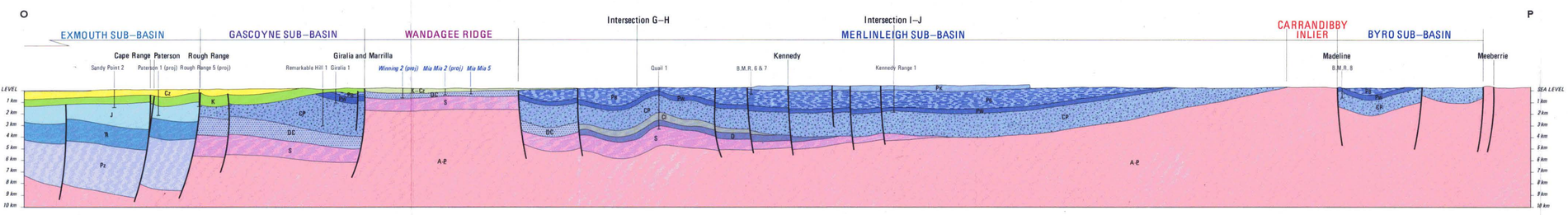




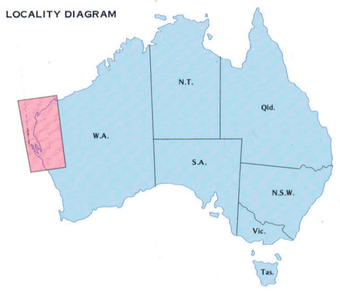








LOCALITY DIAGRAM



DIAGRAMMATIC CROSS-SECTION REFERENCE

- K–Cz — Cz — Cainozoic
- K — Cretaceous
- K–Cz — Cretaceous and Cainozoic, grouped
- J — Jurassic; **DINGO CLAYSTONE** and equivalents, and (in south) **WOODLEIGH FORMATION**
- Tr — TrJ — Middle Triassic – Lower Jurassic; **MUNGAROO, BRIGADIER and NORTH RANKIN FORMATIONS**
- Tr — PTr — Upper Permian – Middle Triassic; **CHINTY FORMATION, LOCKER SHALE**
- Tr — Tr — Triassic; grouped sequence of TrJ and PTr
- PK — Lower to Upper Permian; **KENNEDY GROUP**
- Pe — Lower Permian; **BYRO GROUP**
- Pw — Lower Permian; **WOORAMEL GROUP**
- CP — Upper Carboniferous – Lower Permian; **LYONS GROUP and CALLYTHARRA FORMATION**
- DC — Cl — Lower Carboniferous; **MOOGOOREE LIMESTONE, WILLIAMBURY, YINDAGINDY and QUAIL FORMATIONS**
- D — Devonian
- DC — Devonian and Lower Carboniferous, grouped
- S — Ss — Silurian; carbonate dominant, **DIRK HARTOG and SWEENEY MIA FORMATIONS**
- Sc — Silurian; arenite dominant, **TUMBLAGOODA and KOPKE SANDSTONES**
- S — Silurian; undifferentiated
- Pz — Palaeozoic, undifferentiated
- A-ℰ — Igneous, metamorphic and sedimentary rocks

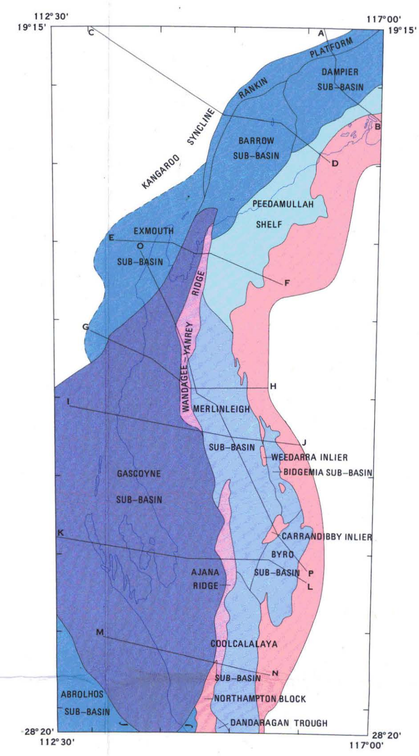
SYMBOLS

- Geological boundary
- Fault, named — Kennedy
- Seismic reflector
- Petroleum exploration well — Kennedy Range 1
- Waterbore, penetrating pre-Cretaceous sequence — *Peron 2*

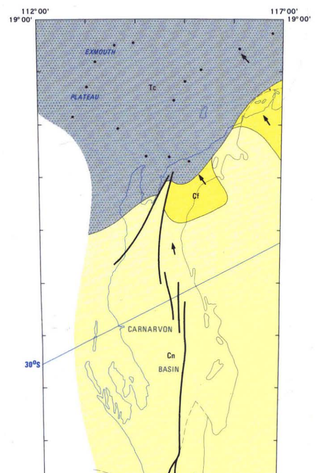
LOCALITY MAP SHOWING DIAGRAMMATIC CROSS-SECTIONS AND SUB-BASIN BOUNDARIES

SCALE 1 : 5 000 000

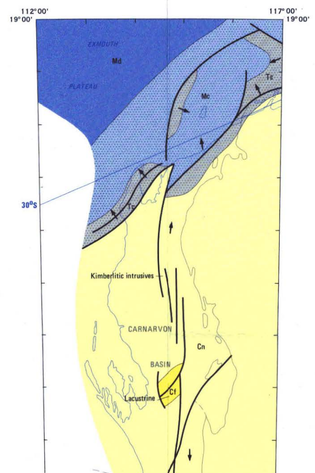
0 100 200 300 KILOMETRES



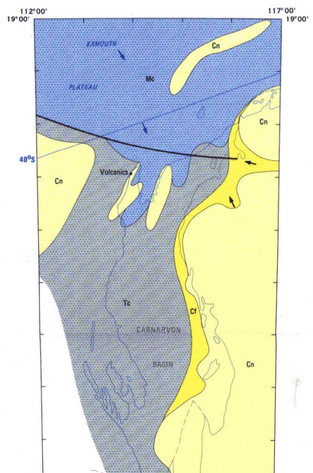
PALAEOGEOGRAPHIC RECONSTRUCTIONS



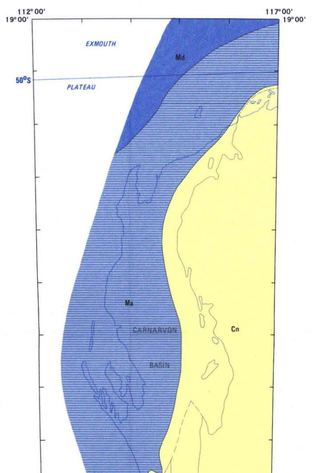
8 LATE TRIASSIC
MUNGAROO FORMATION



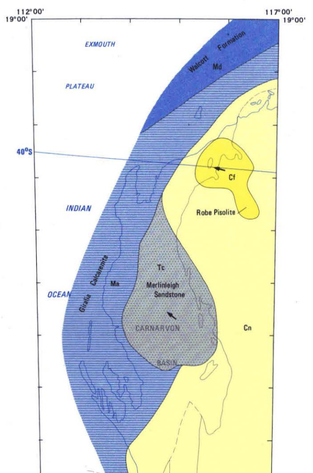
9 EARLY–MIDDLE JURASSIC
DINGO CLAYSTONE and correlatives



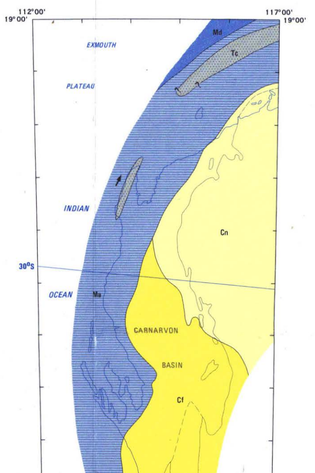
10 EARLY CRETACEOUS (approximately BARREMIAN)
base WINNING GROUP



11 LATE CRETACEOUS (SANTONIAN)
TOOLONGA CALCILUTITE



12 MIDDLE–LATE EOCENE
GIRALIA CALCARENITE WALCOTT FORMATION
MERLINLEIGH SANDSTONE, ROBE PISOLITE



13 MIDDLE MIOCENE
TREALLA LIMESTONE and correlatives

PALAEOGEOGRAPHIC RECONSTRUCTIONS

SCALE 1 : 7 500 000

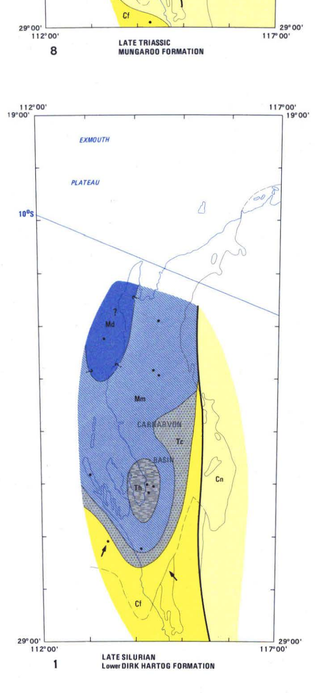
0 100 200 300 KILOMETRES

REFERENCE

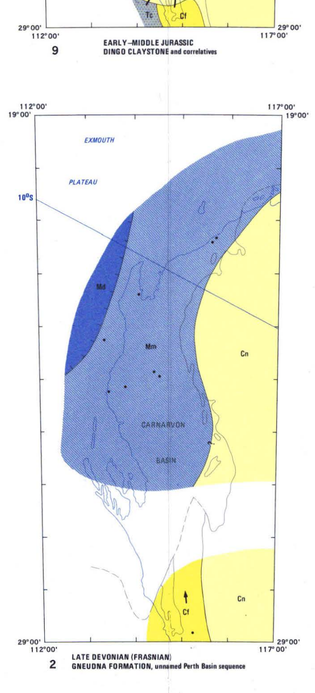
- Not interpreted
- CONTINENTAL
  - Cn — Non-deposition and/or erosion
  - Cf — Fluvial, minor lacustrine
- TRANSITIONAL
  - Tc — Coastal, intercalated continental to shallow marine clastics
  - Th — Evaporitic and/or hypersaline
- SHALLOW MARINE : SHELF AND NEAR SHORE
  - Mc — Clastic
  - Mm — Mixed carbonate and clastic
  - Ma — Carbonate
- DEEPER MARINE : OUTER SHELF TO SLOPE
  - Md — Clastic and carbonate

SYMBOLS

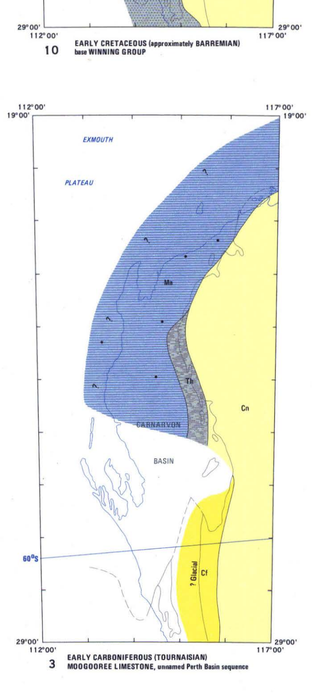
- Environmental boundary
- Active fault
- Direction of sediment transport/clastic influx
- Direction of marine incursion
- Shelf edge
- Approximate palaeolatitude, from Smith and others (1981) or Veevers and others (1984) — 40°S
- Well intersection of relevant age. Only selected wells shown after Palaeozoic



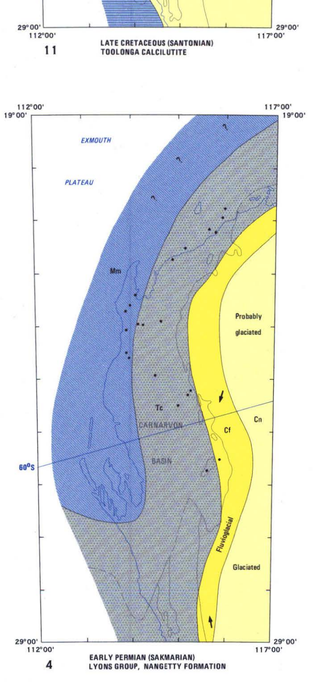
1 LATE SILURIAN
Lower DIRK HARTOG FORMATION



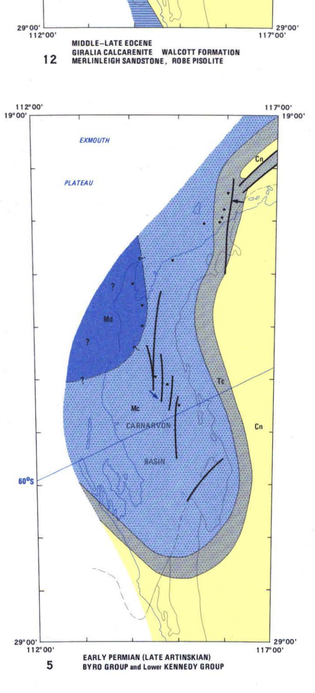
2 LATE DEVONIAN (FRASNIAN)
GNEUDNA FORMATION, unnamed Perth Basin sequence



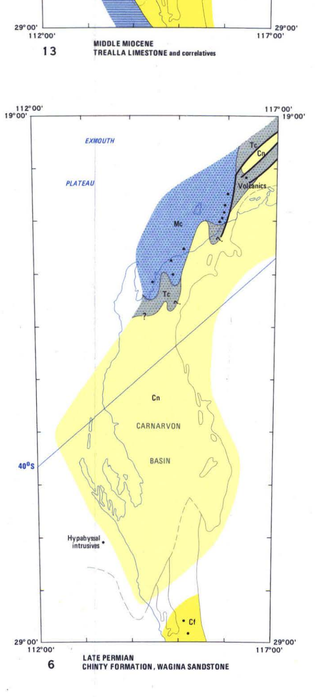
3 EARLY CARBONIFEROUS (TOURNAISIAN)
MOOGOOREE LIMESTONE, unnamed Perth Basin sequence



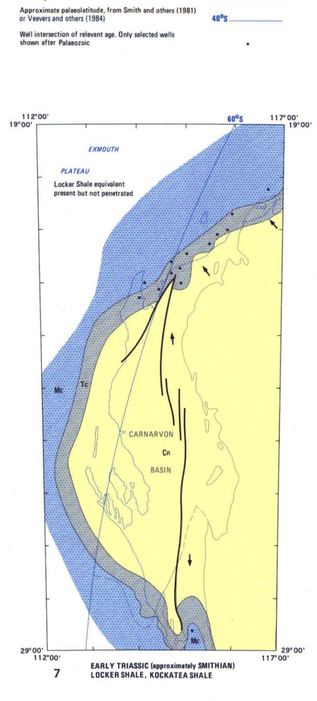
4 EARLY PERMIAN (SAKMARIAN)
LYONS GROUP, NANGETTY FORMATION



5 EARLY PERMIAN (LATE ARTINSKIAN)
BYRO GROUP and Lower KENNEDY GROUP



6 LATE PERMIAN
CHINTY FORMATION, WAGINA SANDSTONE



7 EARLY TRIASSIC (approximately SMITHIAN)
LOCKER SHALE, KOCKATEA SHALE