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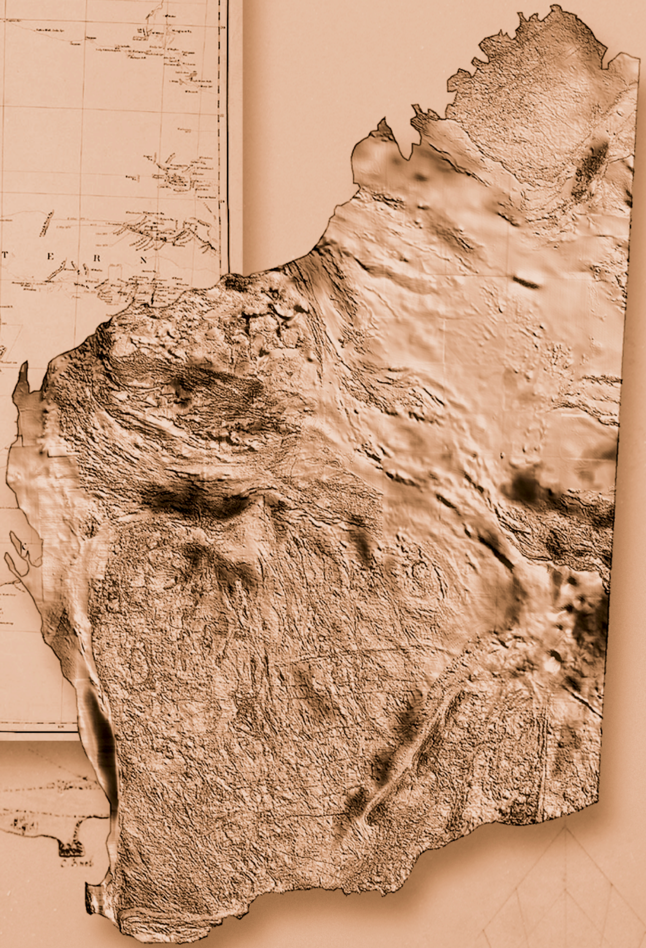
GEOLOGY OF THE SOUTHERN CARNARVON BASIN WESTERN AUSTRALIA — A FIELD GUIDE

by R. M. Hocking



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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GEOLOGY OF THE SOUTHERN CARNARVON BASIN, WESTERN AUSTRALIA — A FIELD GUIDE

by
R. M. Hocking

with contributions from
A. J. Mory

Perth 2000

MINISTER FOR MINES
The Hon. Norman Moore, MLC

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Geology of the Southern Carnarvon Basin, Western Australia — a field guide

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Introduction

This field guide is designed to be used in conjunction with Bulletin 133 of the Geological Survey of Western Australia (GSWA) and with the various maps and Explanatory Notes for the 1:250 000 Geological Series of the Carnarvon Basin. It does not replace them or subsequent reports, but is a guide to some significant outcrop localities in the basin (Fig. 1). Not all significant localities and sections are included, and the degree of detail for each locality varies according to the time since the locality was visited and the author's knowledge of the locality. Where the information or interpretation presented here differs from the Bulletin or Explanatory Notes, this guide presents more recent ideas.

Most sections were measured using eye height and sightings by a Brunton compass, so thicknesses are only accurate to within about 15%. When using this guide, it is important to check details of access with station managers prior to visiting isolated localities. With a few exceptions, the localities are grouped and sequenced by age, and then geographical proximity.

This guide was originally prepared in 1990 (Hocking, 1990a). A new cycle of work by the GSWA has since commenced in the basin (Crostella and Iasky, 1997; Iasky et al., 1998; Iasky and Mory, 1999), and two symposia (Purcell and Purcell, 1994, 1998) contain substantial contributions on the onshore Carnarvon Basin. The sedimentary basins of Western Australia and their subdivisions have also been systematically classified (Hocking, 1994) since 1990. This body of work has resulted in the revision of some aspects of the background geology, particularly with respect to the age and correlation of the 'Silurian' (now recognized as Ordovician) and some revisions to the nomenclature of the Permian succession. Basin subdivisions have also been refined. The revised stratigraphy and correlatons have been incorporated into the text where necessary, primarily by Arthur Mory. There have been few changes in interpretations at the outcrop level, and some localities have been added, based on visits since 1990.

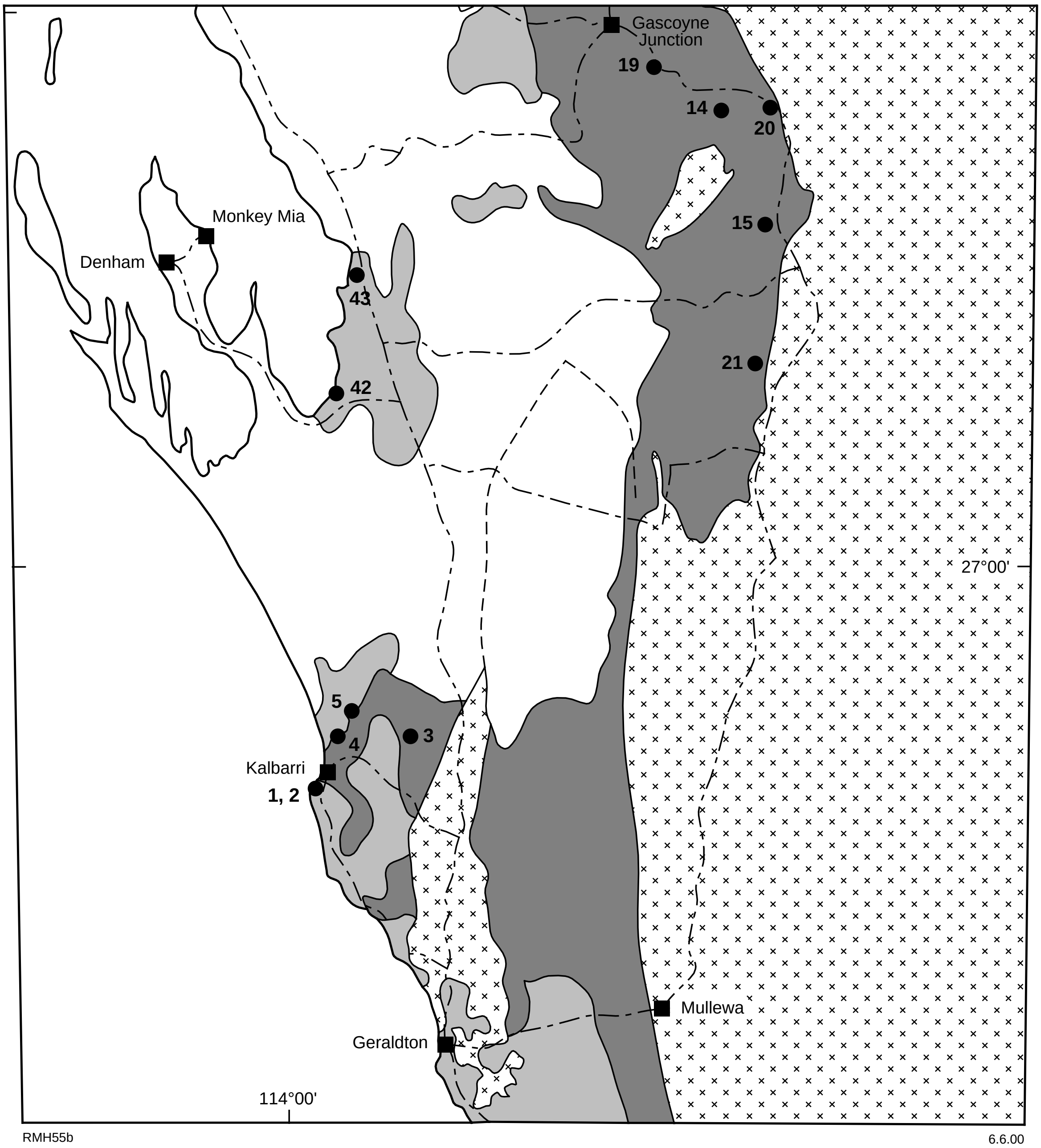
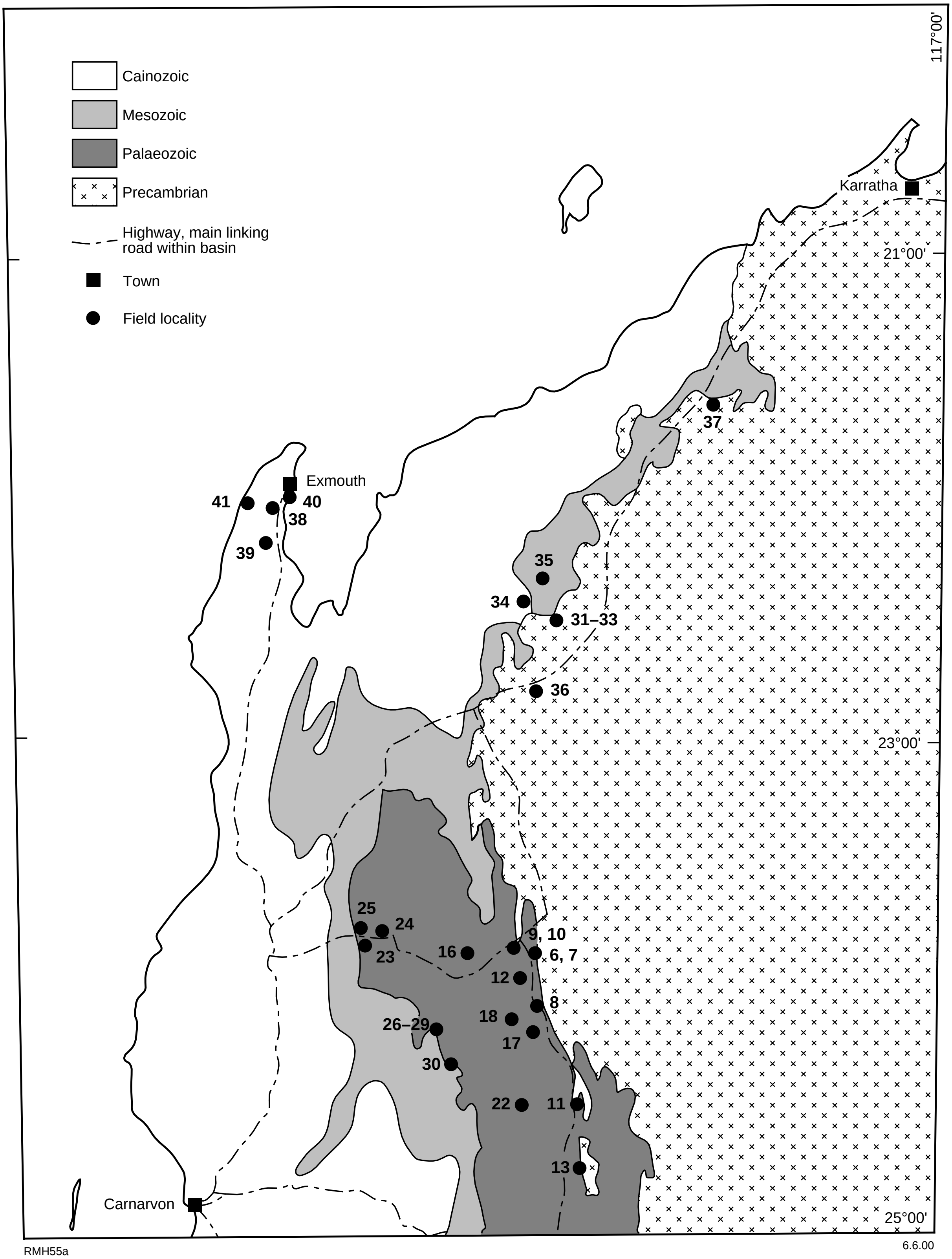


Figure 1. (above and opposite) Field localities, simplified geology, and major access roads, Southern Carnarvon Basin


Cainozoic
Mesozoic
Palaeozoic
Precambrian
Highway, main linking road within basin
Town
Field locality
117°00'
Karratha
21°00'
Exmouth
23°00'
Carnarvon
25°00'
41
40
38
39
37
35
34
31–33
36
25
24
23
16
9, 10
6, 7
12
8
18
17
26–29
30
22
11
13
RMH55a
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Regional geology

Hocking (1994) divided the Carnarvon Basin into the Southern Carnarvon Basin, containing primarily Palaeozoic sedimentary rocks with a Mesozoic and Cainozoic veneer, and the Northern Carnarvon Basin, which was the primary Mesozoic depocentre. These boundaries and subdivisions have been revised slightly as a result of a reassessment of the basin's petroleum prospectivity by the GSWA (Crostella, 1995, 1996; Crostella and Iasky, 1997; Iasky and Mory, 1999). The localities described in this guide lie in the Southern Carnarvon Basin, except for those on the Peedamullah Shelf and Cape Range. The Cretaceous rocks along the western side of Kennedy Range could, however, be thought of as the feather edge of the Northern Carnarvon Basin succession, above the Palaeozoic Southern Carnarvon Basin succession.

Sedimentary succession

Sedimentary rocks in the combined Northern and Southern Carnarvon Basin range in age from Ordovician to Holocene, and can be divided into twelve distinct packages of sedimentary rocks (Fig. 2; Hocking, 1988). These packages reflect major depositional episodes, are primarily unconformity-bounded, and each has unifying lithological characteristics. The packages are based on an analysis of all the Phanerozoic basins in Western Australia (depositional sequences of Trendall and Cockbain, 1990), rather than only the Carnarvon Basin. All the packages can be recognized either in or at the margins of the Westralian Superbasin (North West Shelf; Hocking, 1994); in outcrop, Triassic and Jurassic sedimentary rocks are absent and other intervals are less complete.

The three Palaeozoic packages (Ordovician–Devonian, Late Devonian – Early Carboniferous, and Late Carboniferous – Permian) formed in an intracratonic, northwards-opening basin, which initially developed because of rifting along the coast of Western Australia. They constitute most of the section in the Southern Carnarvon Basin, and have been intersected in marginal areas of the Northern Carnarvon Basin.

The Triassic, Jurassic – earliest Cretaceous, and Early–Late Cretaceous (siliciclastic) packages reflect the development of the Northern Carnarvon Basin as a rift system, related to the breakup of Australia and Greater India. They are pre-rift trough-infill (Triassic); rift valley (Jurassic); and post-breakup, trough-infill, and restricted circulation, trailing-edge successions (Cretaceous) respectively.

The Upper Cretaceous and Cainozoic packages (Upper Cretaceous, Paleocene – Early Eocene, Eocene, Oligocene – Middle Miocene, and Late Miocene – Holocene) are carbonate-dominated, 'trailing-margin' successions that formed by progradation of the continental shelf in the Northern Carnarvon Basin.

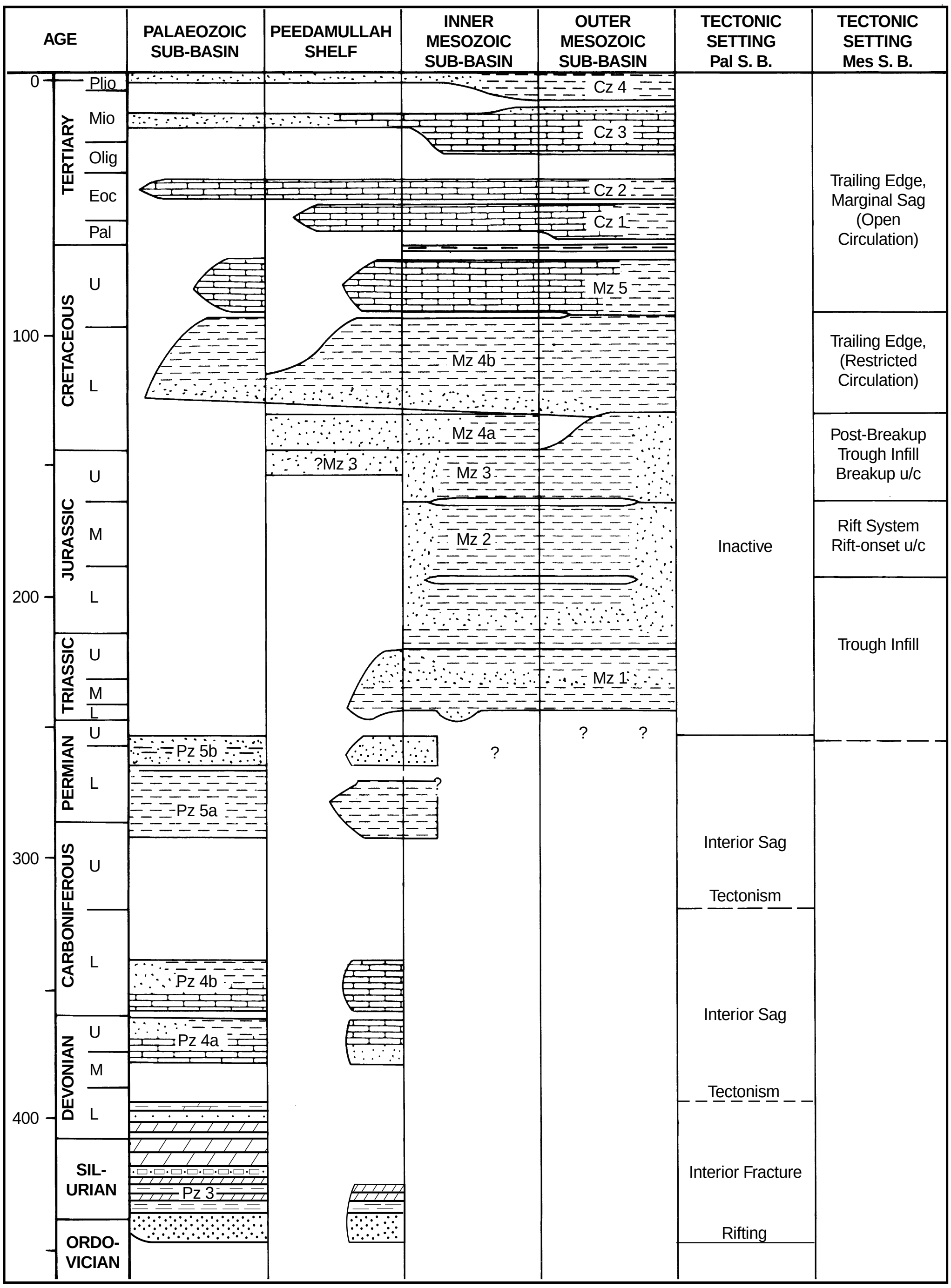
Basin subdivision

The greater Carnarvon Basin extends onshore from Geraldton to Karratha along the western and northwestern coastline of Western Australia (Fig. 3). It covers about 115 000 km^2 onshore and 535 000 km^2 offshore to the continental–oceanic crust boundary. South of 23°S, most major structural elements trend northwards and define a set of sub-basins that contain up to 8 km of predominantly Palaeozoic sedimentary rocks. North of 23°S there is a set of northeasterly trending sub-basins that contain thick Mesozoic and Cainozoic successions above Palaeozoic sedimentary rocks, to a maximum thickness of about 15 km. The southern set consists of the Gascoyne Platform and Merlinleigh and Byro Sub-basins (Fig. 3); these were commonly referred to, collectively, as the 'Palaeozoic sub-basins' (Thomas and Smith, 1976; Hocking, 1988) before Hocking (1994) grouped them as the Southern Carnarvon Basin. The northern set contains the Investigator, Exmouth, Barrow, and Dampier Sub-basins, Kangaroo Syncline, and Rankin Platform (Fig. 3), which were commonly referred to as the 'Mesozoic sub-basins'. The Peedamullah Shelf and Lambert Shelf (Fig. 3) are peripheral areas where a southwards-thinning wedge of Mesozoic sedimentary rocks rests on either Palaeozoic sedimentary rocks (Peedamullah Shelf) or Precambrian rocks (Lambert Shelf). The Bernier Platform, to the west of the Gascoyne Platform, has a thin cover of Mesozoic sedimentary rocks above basement. Collectively they form the Northern Carnarvon Basin.

Structure

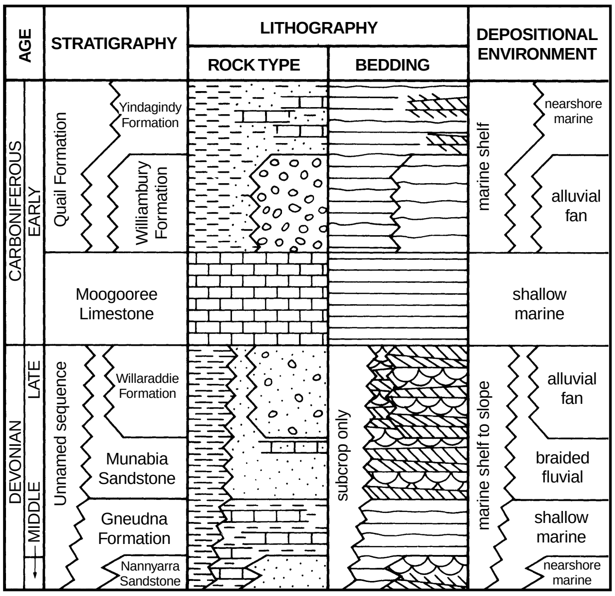
Two gross structural trends are present: a northerly trend in the southern, onshore Carnarvon Basin, and a northeasterly trend in the Northern Carnarvon Basin (Fig. 3). The first trend was present when deposition began in the basin in the Ordovician, and persisted through the Palaeozoic. It is expressed clearly in the orientation of the eastern basin margin, in the component faults of the Kennedy Fault System, in the Wandagee–Yanrey Fault System, and the Darling Fault. The second trend developed in the Triassic, was most active during the Jurassic, and is exemplified by the orientation of the Flinders Fault System, the Rankin Platform, and adjoining structural terraces. A secondary, approximately north–south trend in the northern offshore areas is seen in the orientation of the southwestern extension of the Rankin Platform (the Hilda–Alpha Arch), the Deepdale – Sholl Island Fault System, and in secondary faults along the Rankin Platform. The trend is presumably a continuation, beneath the thick Mesozoic cover, of the north–south Palaeozoic trend from onshore areas.

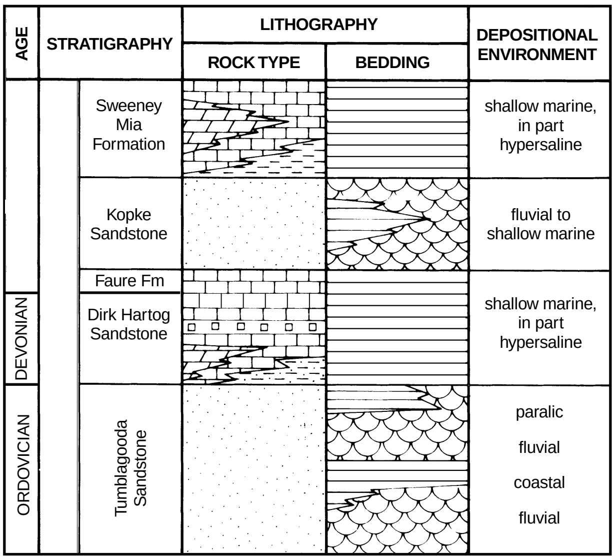
The structural elements in the Southern Carnarvon Basin first developed during Palaeozoic tectonism, and were fully delineated during Triassic–Jurassic faulting. Much of the latter phase consisted of reactivation of older faults. Mid-Carboniferous to Permian rifting along the eastern margin of the Gascoyne Platform is indicated by a succession of this age, up to 5000 m thick,



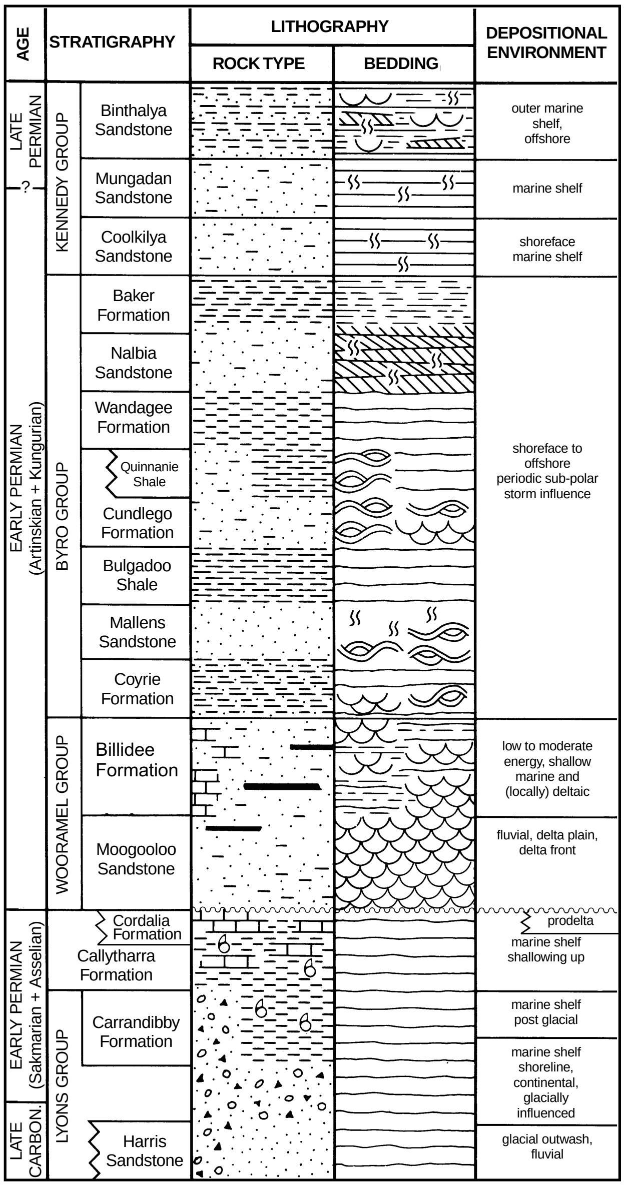
a)

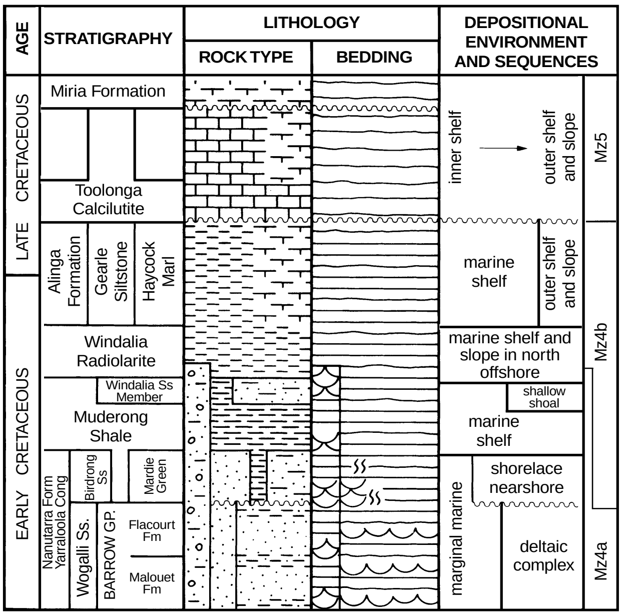
Figure 2. Depositional packages and tectonic evolution of the Carnarvon Basin: (a) sedimentary infill and tectonic development of the Carnarvon Basin. Alphanumeric codes refer to the major depositional packages that can be differentiated in the basin. The codes are placed in the area where each package is most significant (from Hocking, 1988, fig. 3); (b) main stratigraphic units, lithology, and depositional environments for Palaeozoic sedimentary packages, Carnarvon Basin. After Hocking (1990b); (c) main stratigraphic units, lithology, and depositional environments for Mesozoic and Cainozoic sedimentary packages, Carnarvon Basin. After Hocking (1990b); (d) symbols and patterns used on graphic section logs. Additional symbols applicable to specific sections are on those sections

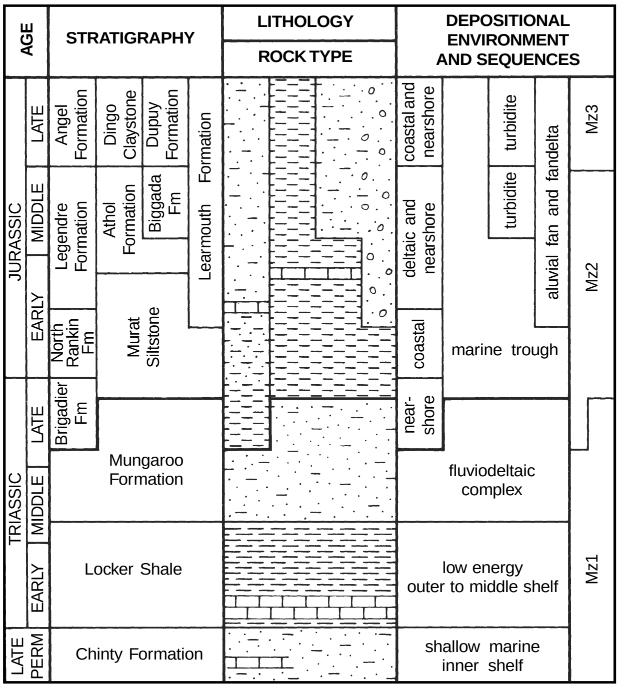

AGE
STRATIGRAPHY
LITHOGRAPHY
ROCK TYPE
BEDDING
DEPOSITIONAL ENVIRONMENT
CARBONIFEROUS
EARLY
Quail Formation
Yindagindy Formation
Williambury Formation
nearshore marine
marine shelf
alluvial fan
Moogooree Limestone
shallow marine
DEVONIAN
LATE
MIDDLE
Unnamed sequence
Willaraddie Formation
Munabia Sandstone
Gneudna Formation
Nannyarra Sandstone
subcrop only
marine shelf to slope
alluvial fan
braided fluvial
shallow marine
nearshore marine


AGE
STRATIGRAPHY
LITHOGRAPHY
ROCK TYPE
BEDDING
DEPOSITIONAL ENVIRONMENT
Sweeney Mia Formation
shallow marine, in part hypersaline
Kopke Sandstone
fluvial to shallow marine
Faure Fm
DEVONIAN
Dirk Hartog Sandstone
shallow marine, in part hypersaline
ORDOVICIAN
Tumblagooda Sandstone
paralic
fluvial
coastal
fluvial

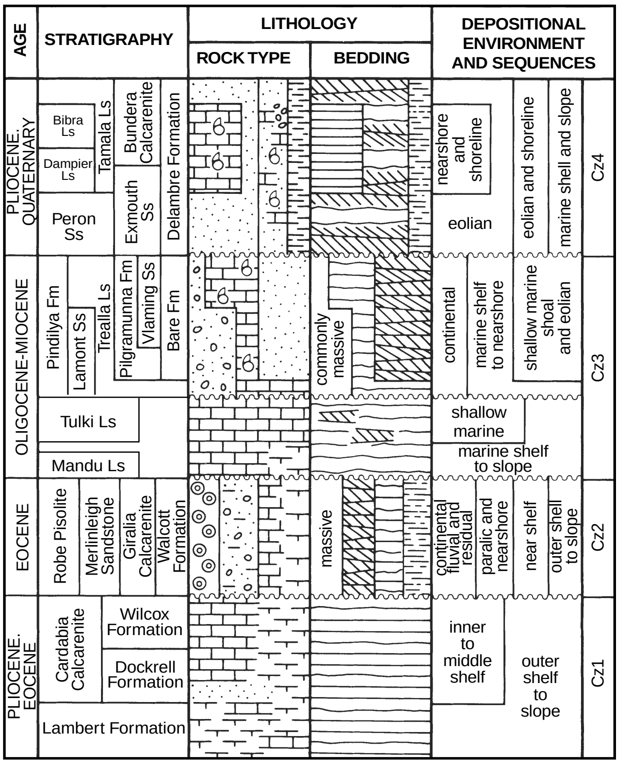
b)

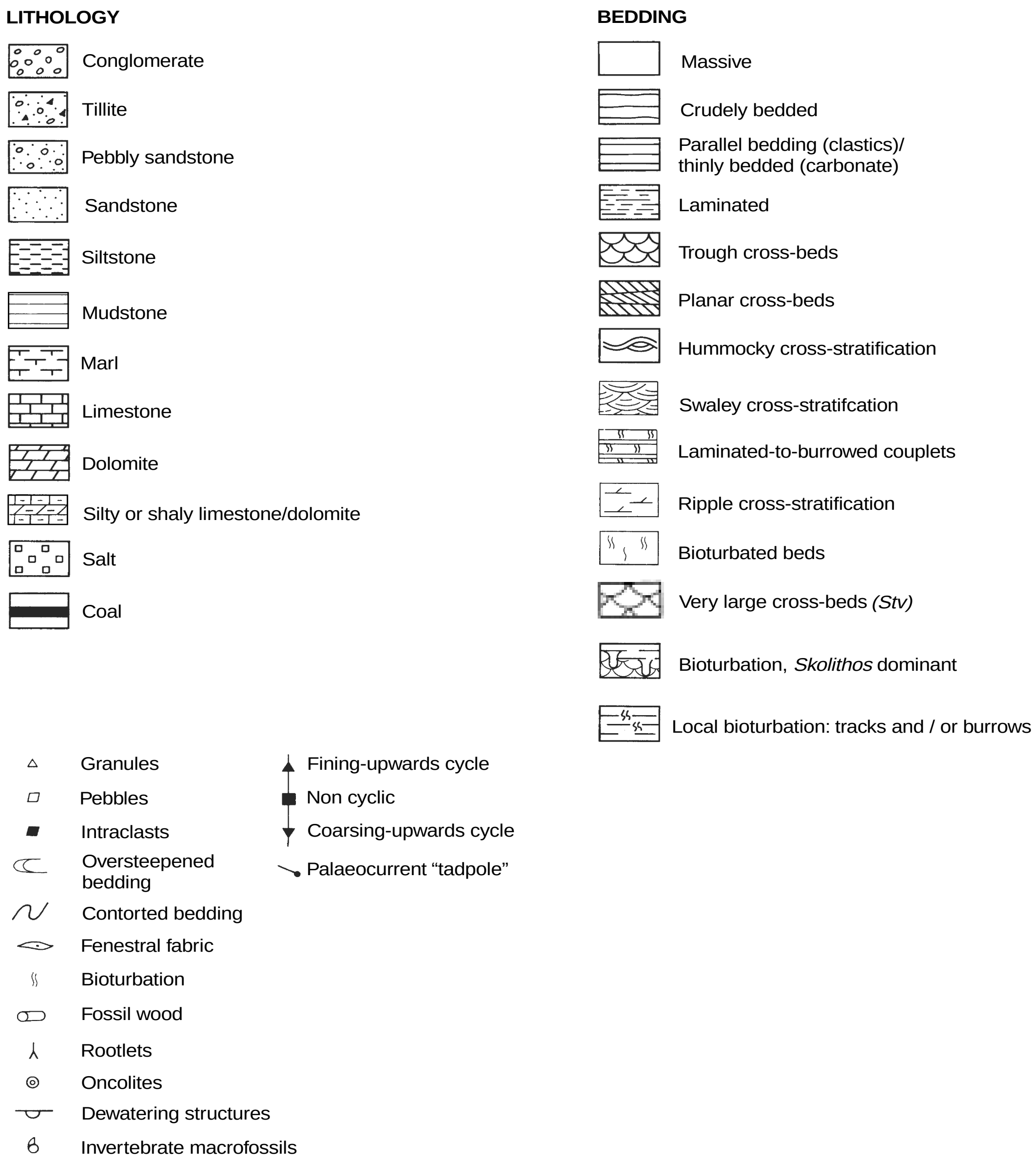

AGE
STRATIGRAPHY
LITHOGRAPHY
ROCK TYPE
BEDDING
DEPOSITIONAL ENVIRONMENT
LATE PERMIAN
KENNEDY GROUP
Binthalya Sandstone
outer marine shelf, offshore
?
Mungadan Sandstone
marine shelf
Coolkilya Sandstone
shoreface marine shelf
EARLY PERMIAN (Artinskian + Kungurian)
BYRO GROUP
Baker Formation
Nalbia Sandstone
Wandagee Formation
Quinnanie Shale
Cundlego Formation
Bulgadoo Shale
Mallens Sandstone
Coyrie Formation
shoreface to offshore periodic sub-polar storm influence
WOORAMEL GROUP
Billidee Formation
low to moderate energy, shallow marine and (locally) deltaic
Moogooloo Sandstone
fluvial, delta plain, delta front
EARLY PERMIAN (Sakmarian + Asselian)
LYONS GROUP
Cordalia Formation
prodelta
Callytharra Formation
marine shelf shallowing up
Carrandibby Formation
marine shelf post glacial
marine shelf shoreline, continental, glacially influenced
LATE CARBON.
Harris Sandstone
glacial outwash, fluvial


AGE
STRATIGRAPHY
LITHOLOGY
ROCK TYPE
BEDDING
DEPOSITIONAL ENVIRONMENT AND SEQUENCES
LATE CRETACEOUS
EARLY CRETACEOUS
Miria Formation
Toolonga Calcilutite
Alinga Formation
Gearle Siltstone
Haycock Marl
Windalia Radiolarite
Windalia Ss Member
Muderong Shale
Nanutarra Form Yarraloola Cong
Birdrong Ss
Mardie Green
Wogalli Ss.
BARROW GP.
Flacourt Fm
Malouet Fm
inner shelf
outer shelf and slope
marine shelf
marine shelf and slope in north offshore
shallow shoal
shorelace nearshore
marginal marine
deltaic complex
Mz5
Mz4b
Mz4a


AGE
STRATIGRAPHY
LITHOLOGY
ROCK TYPE
DEPOSITIONAL ENVIRONMENT AND SEQUENCES
JURASSIC
LATE
MIDDLE
EARLY
TRIASSIC
LATE PERM
Angel Formation
Dingo Claystone
Dupuy Formation
Learmouth Formation
Legendre Formation
Athol Formation
Biggada Fm
North Rankin Fm
Murat Siltstone
Brigadier Fm
Mungaroo Formation
Locker Shale
Chinty Formation
coastal and nearshore
turbidite
aluvial fan and fandelta
deltaic and nearshore
coastal
marine trough
near-shore
fluviodeltaic complex
low energy outer to middle shelf
shallow marine inner shelf
Mz3
Mz2
Mz1

c)


AGE
STRATIGRAPHY
LITHOLOGY
ROCK TYPE
BEDDING
DEPOSITIONAL ENVIRONMENT AND SEQUENCES
PLIOCENE. QUATERNARY
OLIGOCENE-MIOCENE
EOCENE
PLIOCENE. EOCENE
Bibra Ls
Dampier Ls
Tamala Ls
Bundera Calcarenite
Delambre Formation
Peron Ss
Exmouth Ss
Pindilya Fm
Lamont Ss
Trealla Ls
Pilgramunna Fm
Vlaming Ss
Bare Fm
Tulki Ls
Mandu Ls
Robe Pisolite
Merlinleigh Sandstone
Giralia Calcarenite
Walcott Formation
Cardabia Calcarenite
Wilcox Formation
Dockrell Formation
Lambert Formation
commonly massive
massive
nearshore and shoreline
eolian
eolian and shoreline
marine shelf and slope
continental
marine shelf to nearshore
shallow marine shoal and eolian
shallow marine
marine shelf to slope
continental fluvial and residual
paralic and nearshore
near shelf
outer shelf to slope
inner to middle shelf
outer shelf to slope
Cz4
Cz3
Cz2
Cz1


LITHOLOGY
Conglomerate
Tillite
Pebbly sandstone
Sandstone
Siltstone
Mudstone
Marl
Limestone
Dolomite
Silty or shaly limestone/dolomite
Salt
Coal
BEDDING
Massive
Crudely bedded
Parallel bedding (clastics)/ thinly bedded (carbonate)
Laminated
Trough cross-beds
Planar cross-beds
Hummocky cross-stratification
Swaley cross-stratifcation
Laminated-to-burrowed couplets
Ripple cross-stratification
Bioturbated beds
Very large cross-beds *(Stv)*
Bioturbation, *Skolithos* dominant
Local bioturbation: tracks and / or burrows
Granules
Pebbles
Intraclasts
Oversteepened bedding
Contorted bedding
Fenestral fabric
Bioturbation
Fossil wood
Rootlets
Oncolites
Dewatering structures
Invertebrate macrofossils
Fining-upwards cycle
Non cyclic
Coarsing-upwards cycle
Palaeocurrent “tadpole”

d)

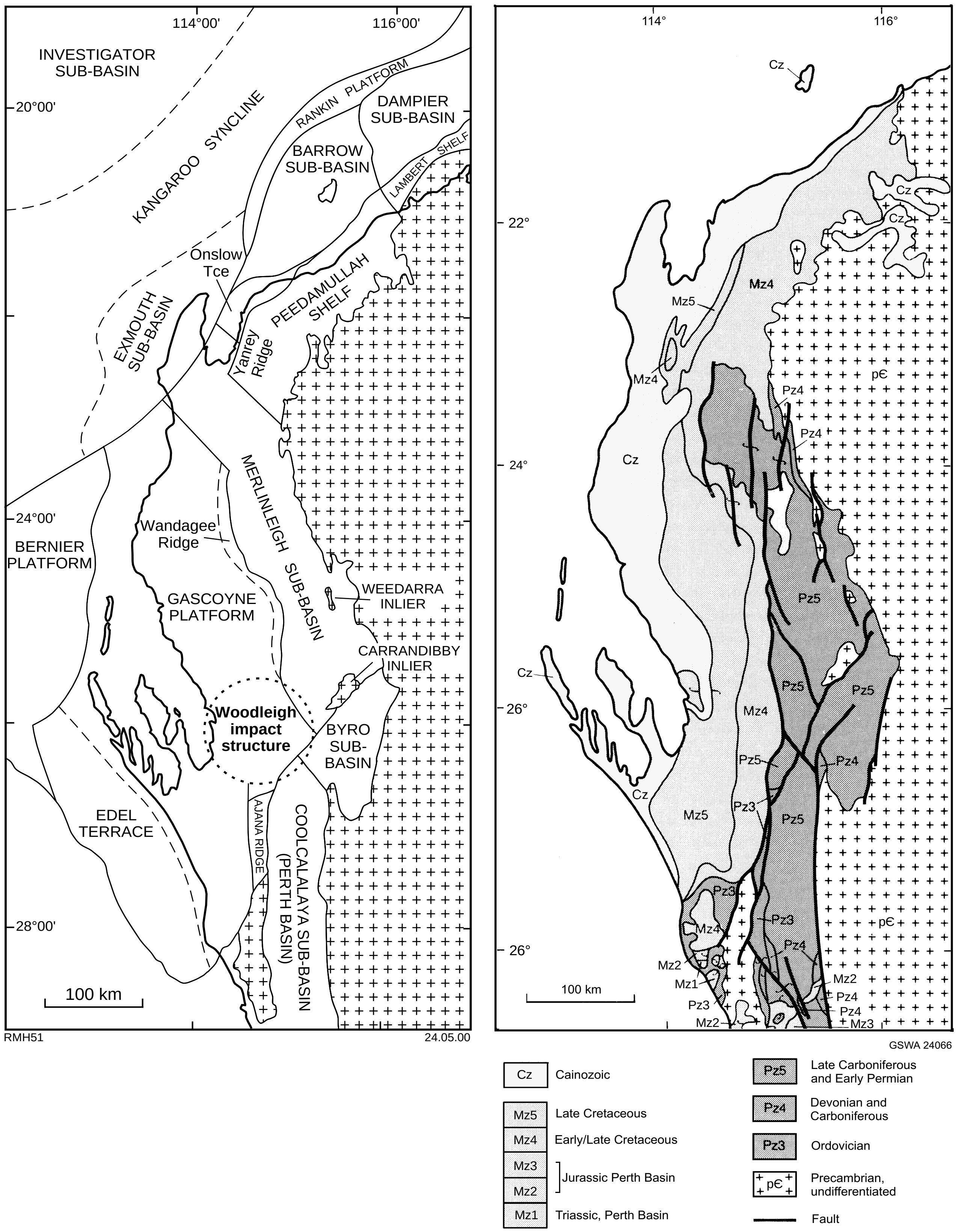


Figure 3. Subdivisions and solid geology of the Carnarvon Basin modified from Hocking (1990b, figs 4-118 and 4-120)

which is confined to the Merlinleigh, Byro, and Coolcalalaya Sub-basins, and that does not extend to the west; maturity modelling of the Lower Phanerozoic on the Gascoyne implies that the mid-Carboniferous to Permian was never deposited there (Ghori, 1998; Iasky and Mory, 1999). Folding in the Palaeozoic succession is relatively minimal except for gentle, broad-scale warping. Most folds are small and related to irregularities in fault planes or to fault drag. In the Mesozoic sub-basins, extensional normal faulting began in the late Permian to early Triassic, and reached a peak in the mid-Jurassic.

Anticlines along the coast north of Carnarvon are commonly referred to as the ‘coastal anticlines’. The largest of these is the Cape Range Anticline. Several islands to the north and east also overlie, and are surface expressions of, anticlines; the largest is Barrow Island. The anticlines are commonly asymmetric and developed as inversion structures due to reverse movement on underlying normal faults; they are drapes over upthrust fault blocks. The movement is largely post-Miocene, although patterns of sediment thinning and lateral facies variations over the anticlines (distribution of Korojon Calcarenite lithofacies, Birdrong Sandstone, and sandstone within the Muderong Shale) indicate that structural inversion extends back to the Cretaceous on some anticlines. Compressional wrench faulting in the Turonian in the Barrow Sub-basin, which Williams and Poynton (1985) attributed to continuing interaction between the Australian–Antarctic and Indian plates, may have caused pre-Miocene inversion. Miocene and post-Miocene inversion is due to the compressive regime set up by the collision of the Australian–Antarctic plate and the Indonesian Arc in the Middle Miocene (Williams and Poynton, 1985).

A notable feature centred directly east of Hamelin Pool is the Woodleigh impact structure, a 120 km-diameter, multi-ring circular impact of pre-Early Jurassic age that is buried below 60–200 m of Cretaceous marine strata and locally Lower Jurassic lacustrine deposits. There is virtually no surface expression of the structure apart from some drainage that implies Cainozoic movements along the outer ring faults, probably activated by Miocene compression (Iasky and Mory, 1999; Mory et al., 2000).

Petroleum exploration

In 1953, West Australian Petroleum (WAPET) struck oil in Rough Range 1. The field was not economic, but led to further exploration (Johnstone, 1979; Wilkinson, 1988). In 1964, WAPET discovered the first commercial oilfield in the basin, at Barrow Island, and in 1971 Burmah Oil Company of Australia (now Woodside Offshore Petroleum) drilled the discovery well for the North Rankin Gasfield. Numerous small fields were discovered in the 1980s; the exploration and discoveries to 1988 are summarized in Purcell and Purcell (1988). Further discoveries are detailed in Purcell and Purcell (1994).

Other publications and revisions

Publications that supplement this revised guide are the GSWA Bulletin on the Carnarvon Basin (Hocking et al., 1987), later summaries (Hocking, 1988, 1990b), the various 1:250 000 maps and Explanatory Notes for the basin (van de Graaff et al., 1980, 1982, 1983; Hocking et al., 1983, 1985a,b; Williams et al., 1983a,b,c; Butcher et al., 1984; Denman et al., 1985), a previous excursion guide (Johnstone et al., 1976), and the Bureau of Mineral Resources (BMR, now Australian Geological Survey Organisation — AGSO) publications (Condon, 1954, 1965, 1967, 1968; Condon et al., 1955, 1956; Konecki et al., 1958), which contain numerous detailed maps of significant areas, fossil lists, and outcrop details.

Several papers on the geology of the onshore Carnarvon Basin were presented at the Western Australian Basins Symposium (Gorter, 1994; Gorter et al., 1994; Purcell and Purcell, 1994; Warris, 1994). The GSWA also commenced a study of the basin focused on the petroleum potential of onshore areas (Crostella, 1995, 1996). Since the field guide was first published in 1990, some localities have been reassessed, and some new localities have been added to the guide. There has been a substantial change to the understanding of the Wooramel Group in the Byro Sub-basin, because of the drilling results of GSWA Ballythanna 1 (Mory, 1996a). In summary, a new sandstone unit has been recognized within the Callytharra Formation, the Ballythanna Sandstone Member, to which many of the outcrops previously thought to be Moogooloo Sandstone belong. Many of the exposures of Keogh Formation are re-interpreted as being a combined section of Moogooloo Sandstone and Keogh Formation or Billidee Formation.

Acknowledgements

This field guide draws on the accumulated work of most of the GSWA personnel who were involved in the mapping of the Carnarvon Basin in the late 1970s: Eric van de Graaff, Peter Denman, Peter Moore, Ian Lavering, and Henry Moors. Other people whose work has contributed to this guide either directly or indirectly are Murray Johnstone, Doug Smith, John Voon, Guy Le Blanc Smith, and Angelo Crostella. Andrew Pitchford's field guide for WAPET was very useful for directions and also descriptions of some localities. Lastly, the comments of participants on the Carnarvon Basin excursions in 1989, 1990, and 1992 are acknowledged.

Kalbarri area: Ordovician and Mesozoic

Background geology

Ordovician: The known history of the Carnarvon Basin began in the Ordovician when the Tumblagooda Sandstone was deposited. Between the Ordovician and mid-Devonian, two major couplets of fluvial to tidal ‘redbed’ sandstone overlain by shallow-marine dolomite, limestone, and evaporites were deposited (the Tumblagooda Sandstone and Dirk Hartog Group; and the Faure Formation, Kopke Sandstone, and Sweeny Mia Formation). The Tumblagooda Sandstone is the only part of this succession that is exposed in the southernmost part of the basin near Kalbarri. In the subsurface, these strata extend through all but the easternmost Carnarvon Basin, and sparse age data suggest that the lower Phanerozoic sucession extends from the Ordovician to the mid-Devonian (Mory et al., 1998). Suggestions since 1990 that the group ranges from Cambrian to Silurian (Gorter et al., 1994; Warris, 1994) were not accepted by Hocking and Preston (1998). Up to the end of the Devonian, the Gascoyne Platform probably had a similar structural evolution to the Merlinleigh, Byro, and Coolcalalaya Sub-basins. After that time, even though the geological record is fragmentary because of erosion, the similarity of the succession to that in the Merlinleigh Sub-basin indicates that deposition was continuous between the two sub-basins until the Early Carboniferous when deposition of the Quail Formation ceased.

The Tumblagooda Sandstone was deposited in alluvial fan, braided-fluvial, and tidal to nearshore-marine environments (Hocking, 1991). Sediment influx was abundant because of periodic faulting along the basin margin. In the Early Silurian, terrigenous influx to the basin lessened after a prolonged period of tectonic quiescence, and the calcareous to dolomitic deposits of the Dirk Hartog Group formed in nearshore-marine to marine-shelf settings. Environments ranged from low to relatively high energy, and salinities from (probably) normal to hypersaline. The depocentre of that succession is near the western side of the platform, with a maximum known thickness of 739 m in Dirk Hartog 17B, and contrasts to the Ordovician depocenter near the Ajana Ridge. This suggests relative uplift along the Wandagee–Ajana Ridge and in the southern Gascoyne Platform, during deposition of the Dirk Hartog Group in the Silurian. Both ridges continued to be positive features throughout the depositional history of the platform. A short hiatus at the end of the Silurian was followed by deposition of mixed siliclastics and dolomite in a shallow-marine environment (Faure Formation). After a minor fall in sea level, there was sand-dominated deposition in a similar setting to that of the Late Ordovician, but with minor dolomite (Kopke Sandstone). The return of a marine environment led to the deposition of a mixed siliclastic–carbonate succession (Sweeney Mia Formation), at least over the central part of the platform. The Lower Devonian has a maximum combined thickness of approximately 900 m. The entire upper surface of the Sweeney Mia Formation is an eroded surface, and the magnitude of the hiatus separating it from later Devonian sedimentary rocks is unknown. The greater extent and different depositional style of the Devonian – Early Carboniferous succession suggest that the hiatus was substantial and was accompanied by considerable erosion.

The Ordovician–Silurian basin was a north–south oriented, north-opening, interior-fracture basin (Kingston et al., 1983), which was located in equatorial to low tropical latitudes (Embleton, 1994). The location and nature of the western margin of the basin cannot be determined from the preserved record within the basin; palaeocontinental reconstructions (Smith et al., 1981; Veevers, 1984) suggest that it was a continental mass that was part of Greater India. Development of the southern part of the basin is probably related to movements along the Darling Fault, a major crustal feature over 1000 km long that controlled deposition of over 12 km of sedimentary rocks in the Perth Basin. Even though much of this deposition was in transtensional regimes, there was only minor strike-slip movement along the Darling Fault, as dyke swarms dated at 755 Ma in both the Northampton Complex and Bangemall Basin have similar polar wandering curves (Wingate and Giddings, 2000).

Tumblagooda Sandstone: The type section of the Tumblagooda Sandstone in the Murchison River gorge is about 1300 m thick, and is divisible into four facies associations: FA1 to FA4 (Hocking, 1991). The associations form in stratigraphic sequence up the type section and delineate two fining-upwards megacycles (FA1 to FA2, and FA3 to FA4). Trewin (1993a,b) presented alternative interpretations of some of the facies associations. The prolific ichnofauna is described by Trewin and McNamara (1995).

Facies Association 1 (FA1) consists of trough cross-bedded, medium- to coarse-grained sandstone with unimodal, northwestwards palaeocurrents. It was deposited as large, sheet-braided, fluvial lobes, and grades upwards into FA2. Facies Association 2 (FA2) contains fine to medium-grained, mostly thin bedded sandstone, which was deposited in a very shallow marine, largely tidal environment when sediment influx to the basin lessened. Laterally extensive, comparatively thin sheets of FA1 are interbedded in the lower part of FA2, and gradually diminish in abundance up the section.

Facies Association 3 (FA3) succeeds FA2 abruptly and is similar to FA1, although it shows fining-upwards cyclicity on a 10–15 m scale. Like FA1, it was deposited in a sheet-braided, fluvial environment by lobes prograding to the northwest, although energy levels were commonly higher than for FA1. Facies Association 4 (FA4) is a cyclic, interdistributary bay sequence that formed adjacent to, and above, the braided-fluvial deposits of FA3. Most of the association consists of fining-upwards cycles, 0.5 – 2 m thick, from medium-grained sandstone to red, commonly bioturbated siltstone. A subaqueous channel complex is present near the top of the association and excellently exposed in the face of Red Bluff.

A fifth association (FA5) is present up-palaeoslope to the east of the Northampton Complex. It is a conglomeratic alluvial fan or proximal braided-fluvial sequence. Stratigraphic correlation between FA5 and the remainder of the Tumblagooda Sandstone is not possible, but it is a logical upslope deposit.

Triassic: Lower Triassic sedimentary rocks are exposed in the coastal cliffs south of Kalbarri. They are part of the Perth Basin succession and do not extend north of Kalbarri.

The Wittecarra Sandstone is disconformable on the Tumblagooda Sandstone, and probably correlates with other sandstones at the base of the Kockatea Shale. It consists of basal conglomerate overlain, in turn, by silty sandstone and siltstone, sandstone, and conglomerate, and is capped by sandstone with plant rootlets. The sandstone is a braided-fluvial deposit that reworked the uppermost Tumblagooda Sandstone and associated soil horizons. Although fossils have not been found within the Wittecarra Sandstone, its stratigraphic position beneath the Kockatea Shale suggests that it is Early Triassic.

The Kockatea Shale consists of a uniform clayey siltstone that contains some ferruginous layers. These layers could be soil profiles or they may originally have been calcareous. The shale is Early Triassic and is the primary source for hydrocarbons in the Dongara and Woodada gasfields. Rare conchnostrachans within the shale indicate that near Kalbarri, it is a brackish lagoonal deposit, unlike the Kockatea Shale further south.

Cretaceous: Cretaceous sedimentary rocks are exposed in the coastal cliffs, in Meanarra Hill, and north of the Murchison River on Murchison House Station. They are part of the Southern Carnarvon Basin succession, and extend less than 50 km south of Kalbarri. The Winning Group and Toolonga Calcilutite are exposed on Murchison House Station, but only the Birdrong Sandstone, the lowermost unit in the Winning Group, is present in the coastal cliffs. The Birdrong Sandstone is a poorly consolidated, reddish to grey, medium- to coarse-grained sandstone of late Neocomian or Aptian age. Most of the sandstone is a shallow-marine to foreshore deposit, although the poor sorting of the Shell House section suggests that at this location, much of the Birdrong Sandstone may be fluvial. The Birdrong Sandstone is the reservoir for some petroleum accumulations in the Northern Carnarvon Basin and the main artesian aquifer in the Southern Carnarvon Basin.

Cainozoic: Tamala Limestone caps the coastal gorges. It is a calcareous eolian deposit that, to the north of Kalbarri, exceeds 300 m thickness; the sea cliffs north of the Murchison River mouth are composed solely of Tamala Limestone. At both Shell House and Red Bluff, it is less than 15 m thick and heavily calcreted. Original bedding has been largely obliterated by the calcretization.

SECTION 41 35m
RED BLUFF

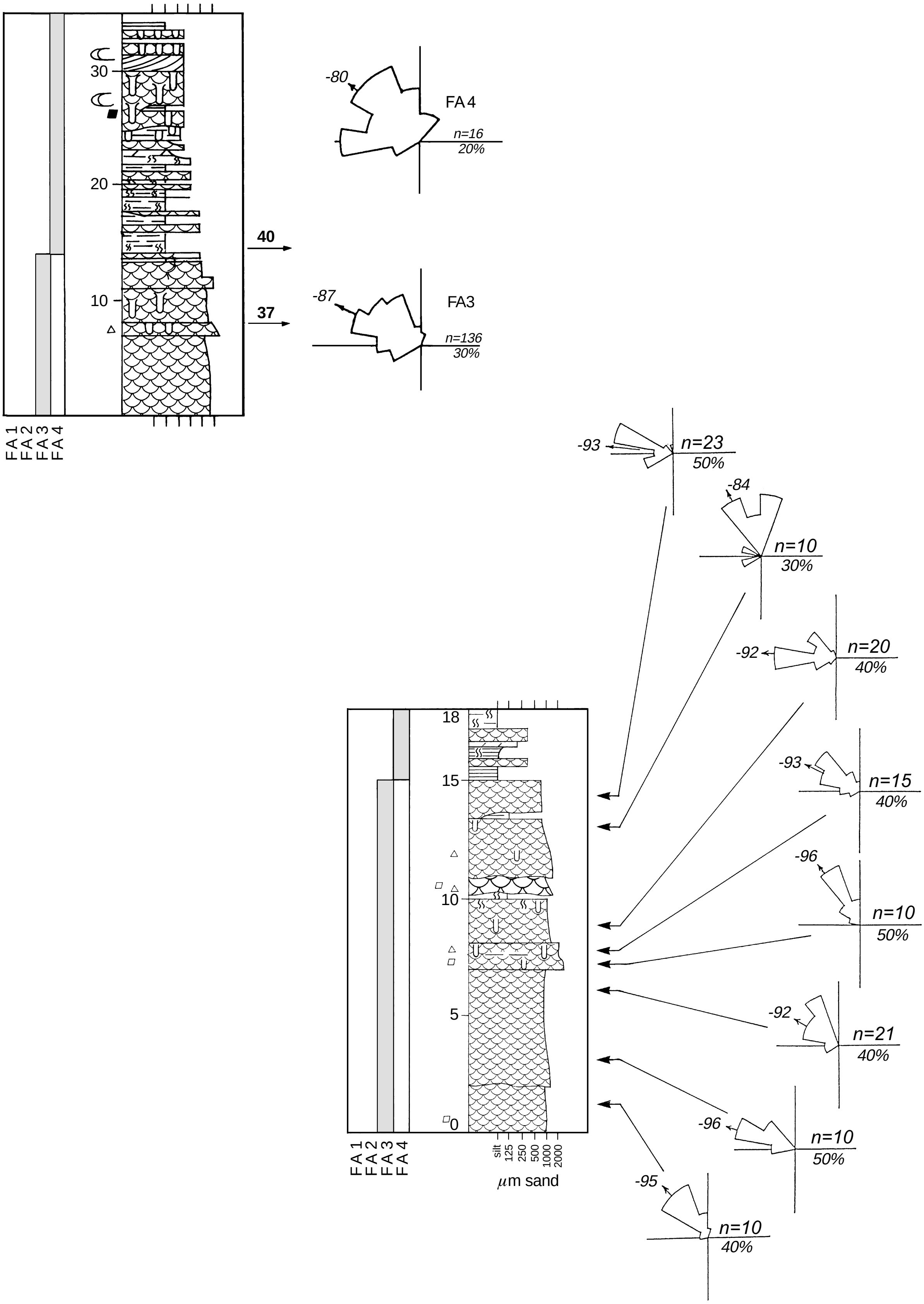


Figure 4. Measured section of the main face of Red Bluff, south of Kalbarri. The lower section is a detailed version of the lower part of the upper section, directly in front of the main face. The Gabba Gabba Member is at 8 m. From Hocking (1991, figs 52 and 94)

Locality 1: Red Bluff

Location: 4 km south of Kalbarri (see Fig. 1).

Access: 4 km south of Kalbarri by signposted, sealed road. Park in the lower carpark at Red Bluff Beach, rather than on top of Red Bluff.

Time: About 1 hour is sufficient to walk around the face of the bluff and see all the major points. Red Bluff is best visited mid- to late afternoon, when the sun will cast an even light on the main face of the bluff.

Notes: Red Bluff is within Kalbarri National Park, so samples cannot be taken without permission from Conservation and Land Management (CALM) based at the park headquarters immediately north of Kalbarri.

Geology: Sections at Red Bluff are shown in Figure 4. From the carpark at the base of Red Bluff (at Red Bluff beach), walk south around the coastal terraces until you are directly in front of Red Bluff. The sandstone belongs to FA3 and is coarse grained, poorly sorted, pebbly, and trough cross-bedded. Palaeocurrents were unimodal to the northwest and very tightly clustered. The Gabba Gabba Member is present just below the uppermost terraces. It is a distinctive pebbly sandstone to pebble conglomerate horizon about 1 m thick, which extends about 40 km along the river and coastal gorges, and can be used as a stratigraphic marker.

Facies Association 3 grades up into FA4 near the top of the terraces by gradually increasing amounts of red siltstone at the top of the fining-upwards cycles. Immediately above the upper, wide platform, FA4 consists of trough cross-bedded sandstone interbedded with laminated to rippled fine sandstone and siltstone. The laminated siltstones and sandstones are distal sheet-flood deposits that were deposited in an interdistributary bay setting. The coarser grained, cross-bedded sandstones were deposited in shallow, rapidly migrating or avulsing channels, or both, within the interdistributary setting. Where bioturbated, sediments were deposited below high-tide level, and where non-bioturbated, above high-tide level and exposed.

A subaqueous channel sequence of *Skolithos*-bearing, cross-bedded sandstone overlies and cuts into the interdistributary sequence. It is best seen from the large fallen block immediately in front of Red Bluff. The presence of more red siltstone at the very top of the exposure suggests the abandonment, avulsion, or lateral migration of the channel sequence.

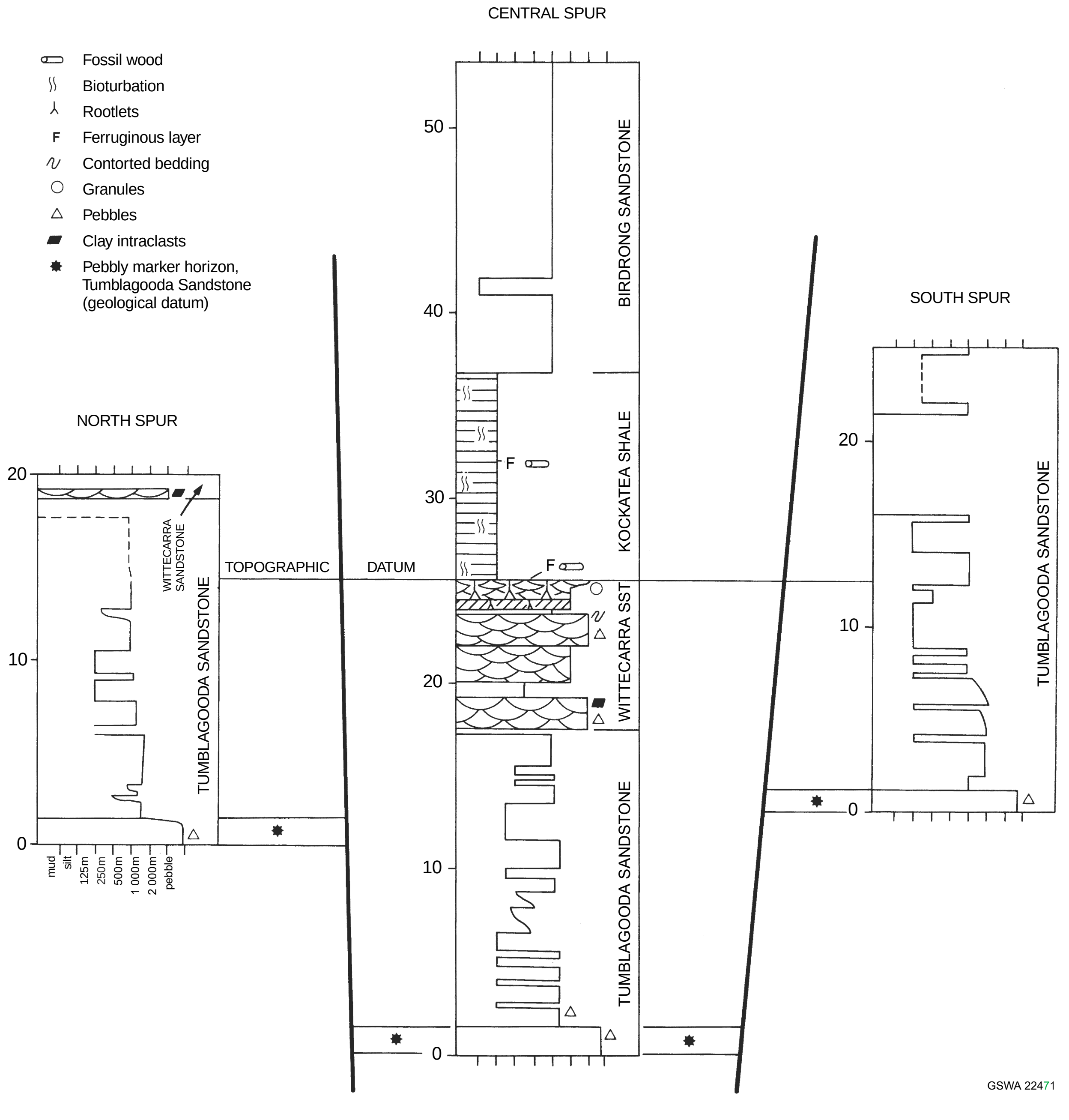


Figure 5. **Simplified representation of sections at Shell House, south of Kalbarri. The Gabba Gabba Member is the pebbly sandstone horizon. From Hocking et al. (1987, fig. 77)**

Locality 2: Shell House

Access: Two-wheel drive. Signposted turn-off to Coastal Gorges from the Kalbarri – Port Gregory road, south of Kalbarri. From the parking area, walk to the southerly facing breakaway about 150 m to the north and climb down. The climbs down and up are steep and involve some scree slopes, so the climb should not be made alone.

Time: Once at the carpark, 60 to 90 minutes is needed to climb down, walk around, and return. Shell House, like Red Bluff, is best visited in the afternoon as it faces west.

Notes: Shell House is within Kalbarri National Park, so samples cannot be taken without permission from CALM (based at the park headquarters immediately north of Kalbarri).

Geology: Shell House contains a small graben complex in the centre spur (Fig. 5). The southern and northern spurs are approximately the same structural level, and the northern fault can be seen in the gully between the central and northern spurs. A brecciated fault zone can also be seen in a small cave at sea level in the front of the central spur. The different levels at which the uppermost *Skolithos*-bearing sedimentary rocks form are the best indicators of the top of the Ordovician and the amount of fault displacement. Triassic sedimentary rocks are present in the central spur only. The late Neocomian Birdrong Sandstone forms a blanket over the graben, which indicates that the graben formed between the Early Triassic and Early Cretaceous.

The Tumblagooda Sandstone at Shell House is similar to the section seen at Red Bluff. The Gabba Gabba Member can be used to determine the throw on the faults that bound the central graben (Fig. 5).

The Wittecarra Sandstone and Kockatea Shale are described in **Background geology** (p. 13), and are best exposed on the southern side of the central spur. The lower contact of the Wittecarra Sandstone can be difficult to identify. The exposure at Shell House represents the northernmost extent of the Perth Basin succession.

The Birdrong Sandstone mantles the Ordovician and Triassic rocks and is easily mistaken for superficial sand, in that it is very poorly consolidated. Ferruginous pisoliths are present at the top of the unit in a weathering horizon about 1 m thick beneath the Tamala Limestone. The outcrop of Birdrong Sandstone at Shell House represents the southernmost extent of the Carnarvon Basin succession.

Locality 3: Z Bend

Location: 36 km northeast of Kalbarri, in Kalbarri National Park.

Access: Two-wheel drive, all weather gravel road. The turn-off to the Z Bend and The Loop is on the northern side of the sealed road from the North West Coastal Highway to Kalbarri, 8 km east of Kalbarri.

Time: About 1 hour should be allowed for the return trip from the main road. A minimum of 90 minutes, preferably 2 – 2.5 hours, is needed at the Z Bend itself. Morning to midday is preferable for light.

Notes: The Z Bend is within Kalbarri National Park, so samples cannot be taken without permission from CALM (based at the park headquarters immediately north of Kalbarri).

Geology: Sections at the Z Bend are shown in Figures 6 and 7. The main tourist lookout is located immediately south of a prominent joint fissure, and consists of a projecting bluff of FA2. While walking down to it from the carpark, FA2 sedimentary rocks are visible on either side. From the lookout, joint control of the Murchison River course is clearly visible. Between 10 and 20 m above the base of the gorge, a thicker bedded lobe of trough cross-bedded FA1 is visible within FA2.

Follow the track behind the lookout to the south, around, and down another major joint fissure. At the base of the gorge there are two large, arcing sets of eurypterid tracks, superimposed on wave ripples. Several sets of wave ripples, some wind adhesion surfaces, and some setulfs can be seen between the trackways and the corner of the gorge below the lookout, below the level of the FA1 intercalation. The typical fine grain size, thin bedding, and variety of bedding types in FA2 are well illustrated.

The sandstone in the FA1 fluvial lobe is medium to coarse grained, locally pebbly, poorly sorted, and trough cross-bedded. Palaeocurrents flowed to the northwest. Contorted bedding is present midway between the two prominent joint fissures on the west face of the Z Bend. At the top of the lobe, there is an interval in which the rock is similar to that below, but palaeocurrent directions are reversed, which indicates reworking by marine currents.

Near the base of the gorge about 100 m downstream from the lookout, there is an northwesterly trending incised channel at the base of the fluvial lobe. This cuts obliquely across the gorge and is best viewed from the northern side. This is one of the few channels seen in the gorges; elsewhere, and above this channel, bedforms are laterally continuous, which indicates sheet braiding. Undercutting and scouring of tidal sedimentary rocks can be seen at the base of the channel on the southern side.

Above the FA1 intercalation below the lookout, there is a large, easterly facing overhang, which commonly has several springs dripping above it. A large, dewatered mound is present in the overhang. The main body of the mound, probably a megaripple, is white sandstone. Capping this is

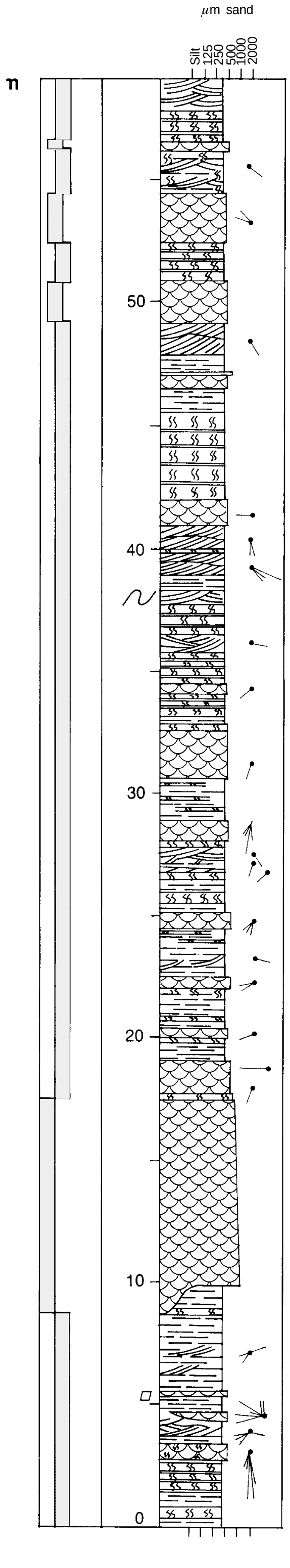


Figure 6. **Measured section, the Z Bend, Kalbarri National Park. Section line is up the joint fissure north of the main lookout. Detailed sections through the FA1 interval near the base are shown in Figure 7. From Hocking (1991)**

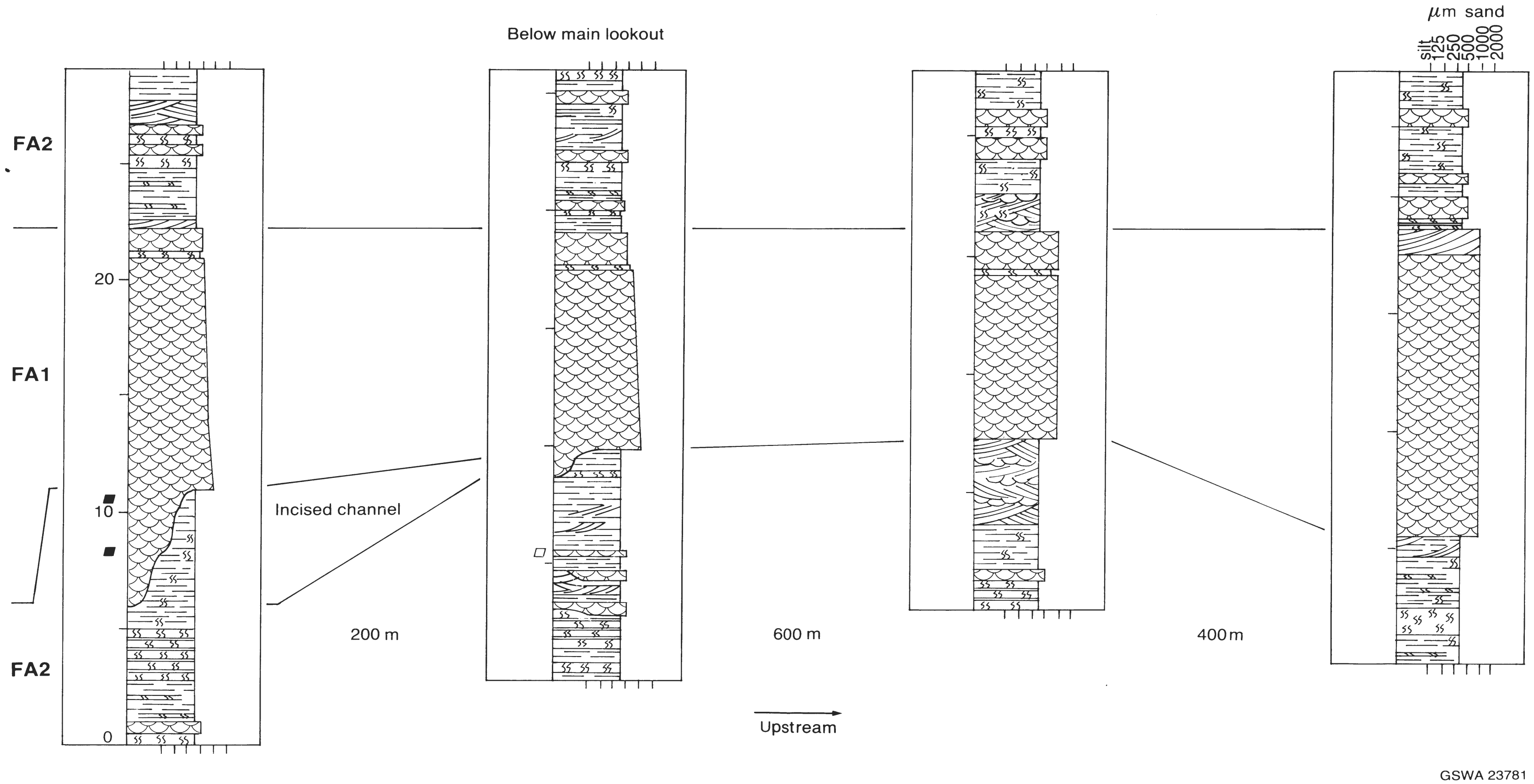


Figure 7. Detailed sections through the FA1 intercalation at the Z Bend. From Hocking (1991, fig. 12)

a red sandstone that has been disrupted and thrust faulted as water and sand escaped from the mound.

From the overhang, go to the downstream corner and climb up the joint fissure to the lookout. Part way up, there is a small exposure of climbing ripples immediately left of the track. These formed in conditions of high supply and are common in FA2.

Locality 4: Stone Wall

Location: Murchison House Station, about 8 km north of Murchison River (see Fig. 1).

Access: Dual-range four-wheel drive only. Drive into Murchison House Station (turn-off on northern side of Kalbarri – North West Coastal Highway road, about 5 km east of Kalbarri) and cross the river at the homestead. Drive 500 m up the hill on the main track to intersecting gates and a small laterite outcrop. Turn right and proceed northwards on the main track over the broad sandy rise. Continue north 5 km to the first major open-valley near river level, where stratigraphically low exposures of FA3 can be inspected a few hundred metres to the west (up-slope towards the main bluffs). Continue north another 2 km to the next major valley, cross the major gully, and take the first left-hand branch. Follow this up the valley to a small dammed spring and yard immediately in front of the major breakaway.

Time: About 60 minutes return trip from the main road, with 90 minutes to 2 hours needed to inspect the section.

Notes: Permission is needed from Murchison House Homestead to enter the property — ring either the Kalbarri or Perth number prior to arrival. Because the locality is on the northern side of the Murchison River, it may be inaccessible if the river is flowing, so it is advisable to enquire about the river height.

Geology: The upper part of the Tumblagooda Sandstone, the complete Winning Group, and the Toolonga Calcilutite are present in creek and breakaway sections immediately above the springs at Stone Wall. Walk up the creek next to the dam and spring to start.

The Tumblagooda Sandstone exposed here is primarily FA3 (Fig. 8). Facies Association 4 is present at the top of the Ordovician section, but is not well exposed. The section consists of poorly cyclic, coarse-grained, trough cross-bedded sandstone, and is typical of the upper part of FA3. The Gabba Gabba Member is present about 20 m above the base of the section, shortly above the first terrace level. Scattered vertical burrows (*Cylindricum*) first appear at about the level of the member, and palaeocurrent directions abruptly shift from 300–350° below the marker to 230–280° above the marker.

The best section of the Birdrong Sandstone (the lowest unit in the Winning Group) in the Kalbarri area is at Stone Wall. The right-hand gully at the top of the Tumblagooda Sandstone has more continuous exposure. It consists of 33 m of very poorly consolidated to unconsolidated, light-grey quartz sandstone, which could initially be mistaken for Quaternary slope deposits. The lower 12 m is massive to very poorly horizontally bedded and dominantly coarse grained. This is overlain by 15 m of indistinctly cross-bedded, medium- and coarse-grained sand, 4 m of very coarse grained sand and, at the top, 2 m of clayey, fine sandstone. Lightly silicified fossil wood with *Teredo* borings has been found at the top of the Birdrong Sandstone. Deposition is assumed to have been in shoreface to coastal environments; the section itself does not have many

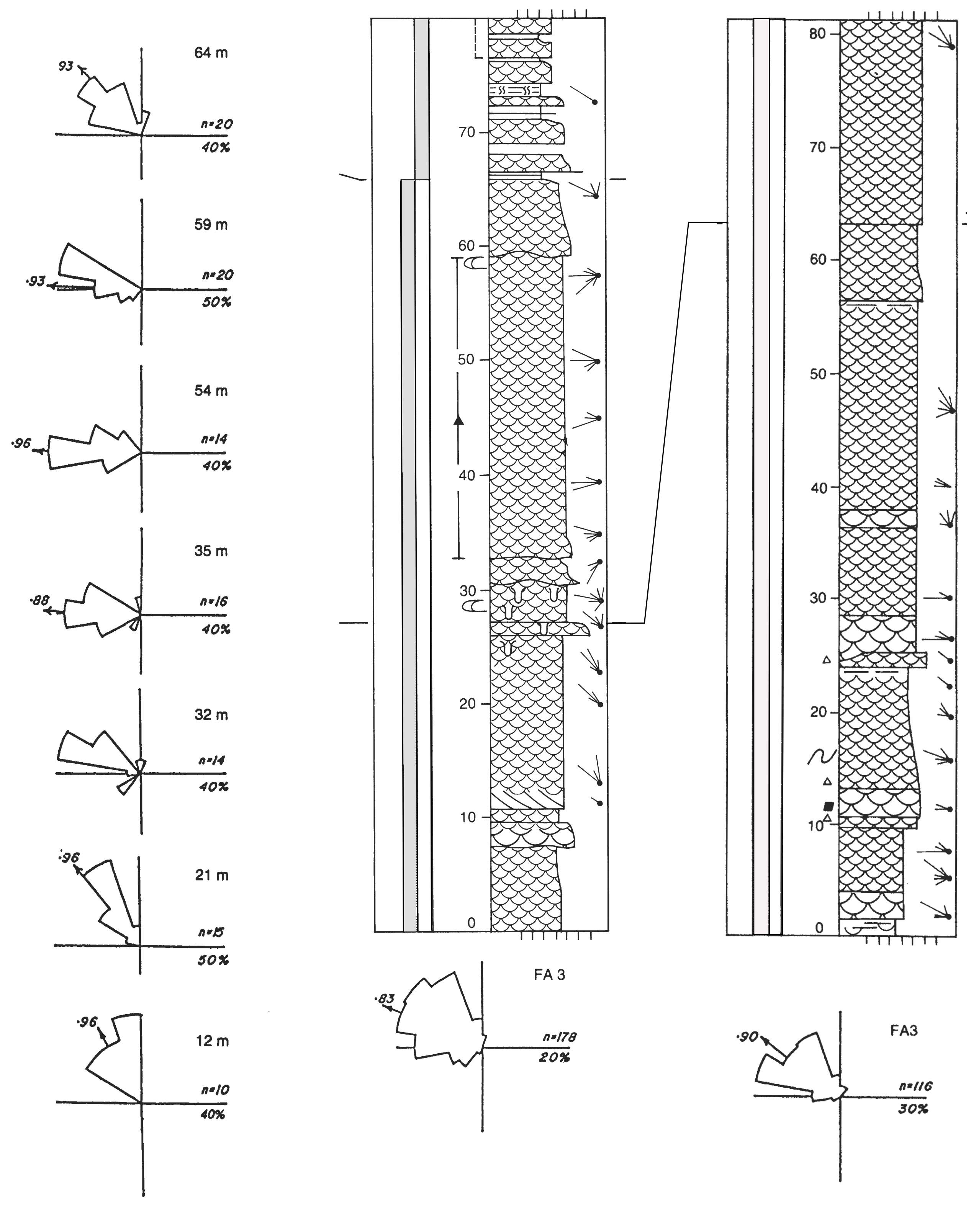


Figure 8. Measured sections of Tumblagooda Sandstone, Stone Wall (left) and Bracken Point (right), Murchison House Station. At Stone Wall, the Gabba Gabba Member is at 26 m. The Gabba Gabba Member does not extend as far north as Bracken Point, but the corresponding stratigraphic level is at 64 m. The section consists solely of FA3. The lower part of the section, in the vertical bluffs and gullies, is shown in detail in Figure 9. From Hocking (1991)

environmentally diagnostic features. Numerous pleosaur bones, sufficient for reconstruction of a skeleton, have been recovered from the top of the sandstone in the southern gullies at Stone Wall.

The Birdrong Sandstone is overlain by hard beds of radiolarian siltstone, which belong to the Windalia Radiolarite. These are characteristically distinguishable by their low density (samples feel light), and that they form minor bluffs in the section. The first large gully past the spur to the north of the Birdrong Sandstone contains a good section of both the Windalia Radiolarite and Alinga Formation. The Windalia Radiolarite is about 25 m thick and overlain, in turn, by soft glauconitic claystone of the Alinga Formation. The section of Alinga Formation is about 15 m thick, and is one of the few complete sections of the unit in the Kalbarri area, because it is mostly obscured by landslides. Both the Alinga Formation and Windalia Radiolarite are low-energy, subwave-base, marine-shelf to offshore deposits.

The Toolonga Calcilutite rests disconformably on the Alinga Formation. The contact is locally marked by phosphate nodules. It is about 25 m thick and consists primarily of very fossiliferous, white-weathering calcilutite and calcisiltite. Small fragments of *Inoceramus*, a giant bivalve, are very abundant and tend to ‘mask’ other fossils. The formation was deposited below wave base on a low-energy marine shelf, after global oceanic circulation had adjusted as a result of Gondwana fragmentation to a situation of minimal terrigenous influx along the Western Australian coastline.

Locality 5: Bracken Point

Access: Dual-range four-wheel drive only. Continue north from the turn to Stone Wall, past the end of the prominent white bluffs to Toolonga Point and the fence near Woonana Spring. Drive north through the gate and continue about 3 km to Bracken Point. The nearest access is from a track that climbs up the broad sand ridges in the gorge.

Time: Assuming it is visited at the same time as Stone Wall, an extra 30–40 minutes drive (return) is needed.

Notes: Permission is needed from Murchison House Homestead to enter the property — ring either the Kalbarri or Perth number prior to arrival. Because the locality is on the northern side of the Murchison River, it may be inaccessible if the river is flowing, so it is advisable to enquire about the river height.

Geology: The section at Bracken Point is a long distance north of Stone Wall on a track that is very rough in places, but contains excellent lateral and vertical exposures of fining-upwards cycles in FA3 (Fig. 8, right). The best of these are approximately 200 m west of the track in a large, high, northerly facing breakaway (Fig. 9). Structures in the section include giant cross-beds, possible antidunes, intraclasts, and complete fining-upwards cycles with three-dimensional exposure.

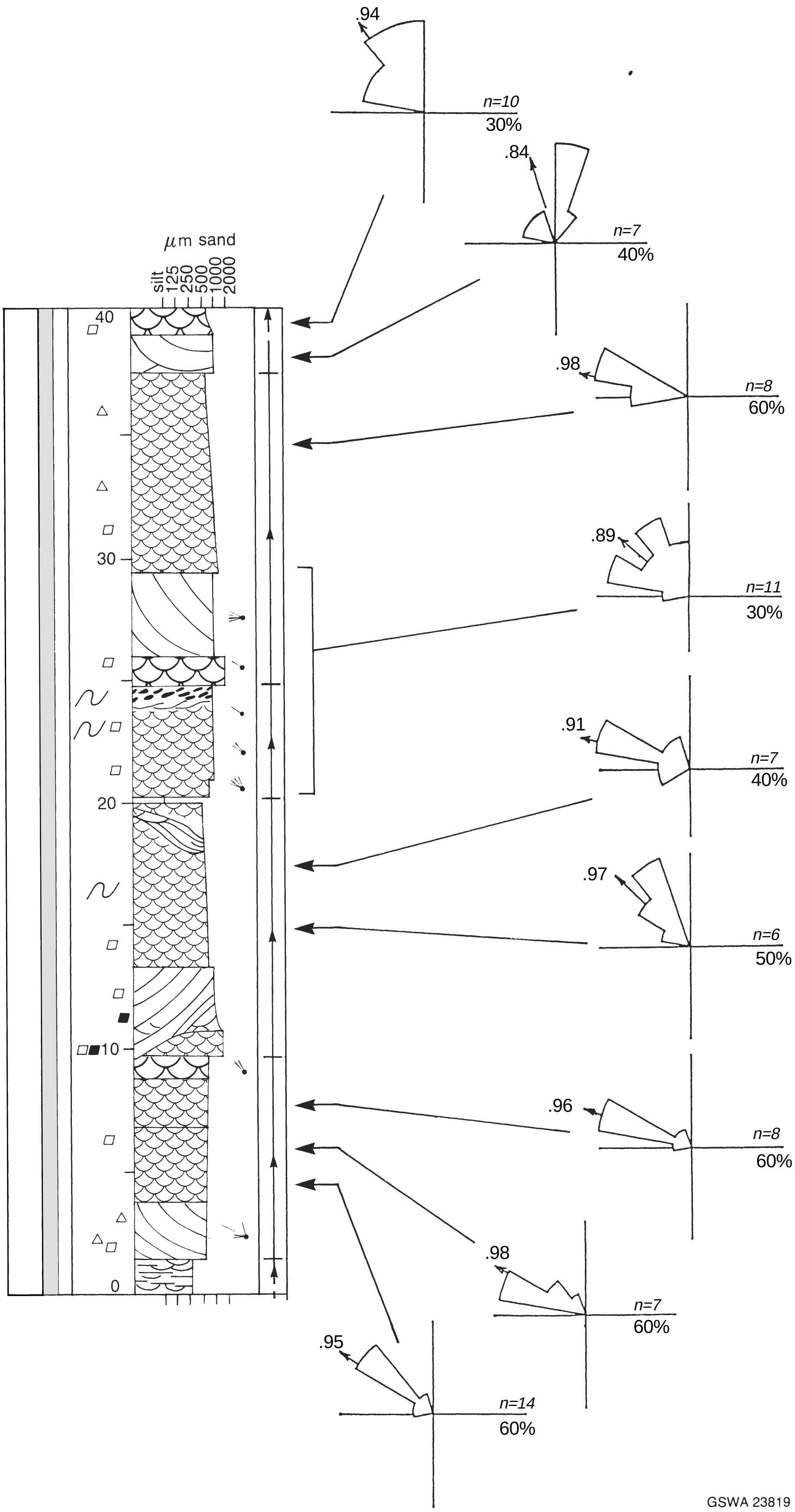


Figure 9. Detailed measured section, Tumblagooda Sandstone, lower part of section at Bracken Point. The large cross-bed below 30 m is in the face of the large vertical bluff. From Hocking (1991, fig. 50)

Merlinleigh Sub-basin: Devonian and Lower Carboniferous

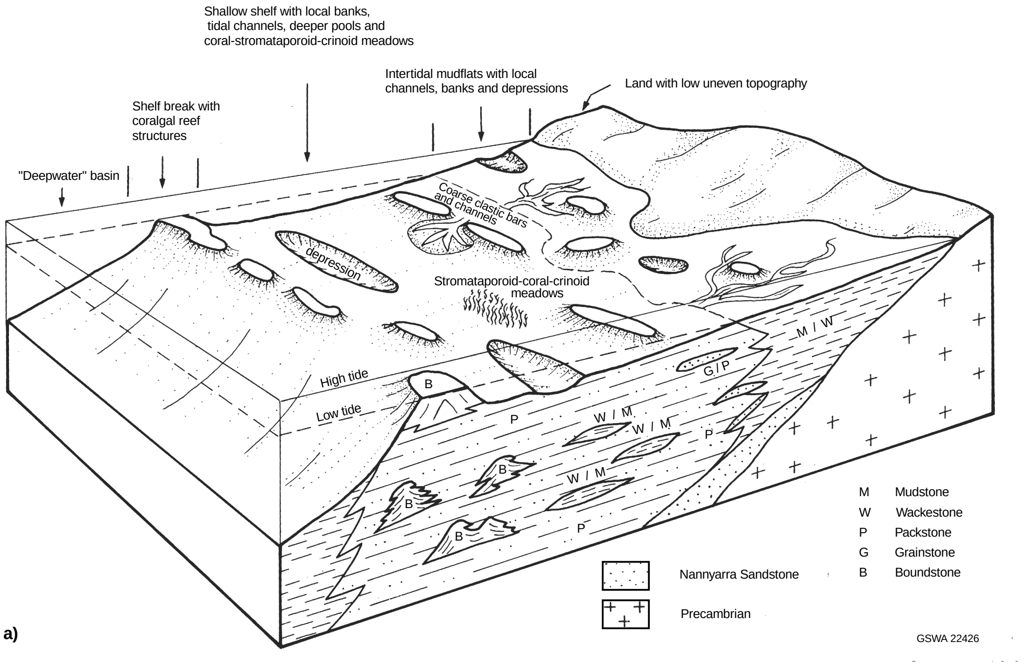
Background geology

The second phase of deposition in the Carnarvon Basin extended from the Middle Devonian to the late Early Carboniferous. There was a minor hiatus in the latest Devonian to earliest Carboniferous, which serves to differentiate two subcomponents. Both are dominated by marine-shelf to nearshore, calcareous and siliciclastic deposits.

Devonian and Carboniferous sedimentary rocks outcrop along the eastern margin of the Merlinleigh Sub-basin between approximately 23°30'S and 24°30'S, and in the subsurface north of approximately 25°S. The most northerly intersections are on the outer Peedamullah Shelf. Their extent offshore to the west is unknown, as the only relatively distal well is Pendock 1. The basin geometry remained similar throughout deposition of the succession. The Devonian–Carboniferous basin was an interior-sag basin (Kingston et al., 1983) that had onlapping margins and minor faulting at, or near, the margins, and was located at 25° to 30°S palaeolatitude (Embleton, 1984). The eastern margin of the basin was in a similar position to the present-day margin, and deposition probably extended northeastwards around the Pilbara Block, into the Canning Basin.

Devonian: The Devonian succession has a cumulative thickness of 1500 m. Significant deposition commenced during a Givetian transgression, when most of the Nannyarra Sandstone was deposited as a diachronous, shoreline sand-prism. Remnants of an earlier fluvial channel-fill, sand-dominated deposit (also included in the Nannyarra Sandstone) are locally preserved. As terrigenous influx lessened, there was a gradual transition from sandy to intermixed silty and calcareous deposition (lowermost Gneudna Formation). Most of the Gneudna Formation formed on a relatively stable, wave-affected, broad shelf that deepened to the northwest (Fig. 10a). Back-reef, platform facies rocks (the Point Maud Member) are present in Pendock 1 and GSWA Barrabiddy 1A (Mory and Yasin, 1999), and indicate that reefs probably developed near the seaward edge of the shelf. Sand influx due to local fault movement near the basin margin led to deposition of the Munabia Sandstone in sandy nearshore to beach and back-beach environments, and then the Willaraddie Formation as coastal fan deltas. West and north of the Merlinleigh Sub-basin, argillaceous and calcareous deposition continued in marine environments.

Early Carboniferous: The Carboniferous succession is up to about 600 m thick. The Moogooree Limestone was deposited on a broad, shallow-marine ramp where there was minimal terrigenous input (Fig. 10b). This environment was locally hypersaline near the basin margin (Radke and Nicoll, 1981), possibly due to the development of carbonate banks, which restricted circulation. Renewed tectonic activity led to the development of alluvial fans along the basin margin (Williambury Formation) in the late Tournaisian. Some terrigenous material was transported further west, to be deposited under marine-shelf conditions as the Quail Formation. Diminution of terrigenous influx in the early Visean, coupled with a return to transgressive conditions, led to



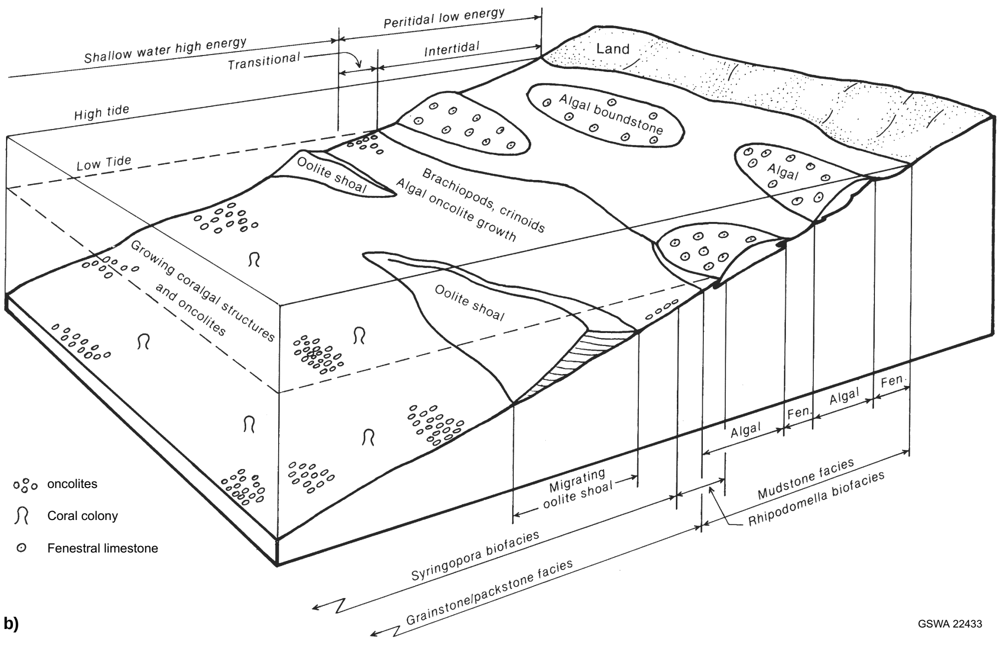


Figure 10. Depositional models for the Gneudna Formation (top) and Moogooree Limestone (bottom; from Hocking et al., 1987, figs 32 and 39): (a) depositional model for the Gneudna Formation. The intertidal zone is mainly mudstone and wackestone, with coarser material in tidal channels and banks and finer material in depressions. The shallow shelf zone is mainly bioturbated packstone deposited at a water depth of up to 10 m. Coarse grainstone forms in bars and small tidal deltas. Finer sediment accumulated in depressions and quiet meadows; (b) depositional model for the Moogooree Limestone. Intertidal zone was low energy with fenestral or cryptalgal laminated mudstones. Subtidal zone was moderate to high energy and grainstones were accumulated. Oolitic shoals and oncolite beds migrated along the sea floor, possibly as shoals. Metahalene to hypersaline salinities reduced fauna and flora, with only isolated colonial corals and crinoids in deeper depressions. Shoals of brachipod shells accumulated near the strandline

mixed siliciclastic–carbonate deposition near the basin margin (Yindagindy Formation), while deposition of the Quail Formation continued further west.

Prior to deposition of the Upper Carboniferous – Lower Permian succession, there was a major period of tectonism in the mid-Carboniferous, during which sedimentary rocks were faulted and folded up to 20° along northerly trending axes. Many of the small- and medium-scale structural elements of the onshore Carnarvon Basin formed at this time.

Locality 6: Nannyarra Sandstone and Gneudna Formation type sections

Location: Williambury Station; 23°58'10"S, 115°12'40"E to 23°58'20"S, 115°12'20"E.

Access: From Moogooree, drive 1.6 km on the Mount Sandiman road to just east of the Moogooree Limestone ridge. Turn left (northeast) onto the track to One Mile Well and cross the Minilya River. At 1 km, turn left (north) onto the track to Red Hill Well and drive 4.6 km to an east–west fence and gate. The track runs along the top of the Gneudna Formation, just west of a range of Munabia Sandstone. This route is shown by Mory (1996b, fig. 1, bottom). Go through the gate, turn east and then north along a north–south fence. Turn east through a strainer gate in the fence, bear southeast for about 500 m to avoid a large, southerly draining gully in the Gneudna Formation, then bear northeast about 500 m towards a sandstone hill due east of the broad Gneudna Formation hill. The sandstone hill is the Nannyarra Sandstone type section. It may be possible to follow a 'geologists' track' after the strainer gate.

An alternate route is via the access road to the gas pipeline 7 km south of Williambury. Continue past the tower on the pipeline towards Gneudna Bore, but turn south where the track swings north. Moderately well-marked vehicle tracks run along the eastern side of the range to GSWA Gneudna 1.

Time: Allow 30 minutes to drive to the base of the Nannyarra Sandstone section from the Moogooree turn-off. About 90 minutes to 2 hours is the minimum time required to examine the Nannyarra Sandstone section, and drive and walk over the Gneudna Formation section.

Notes: Advise either Moogooree or Williambury Homestead before entry.

Geology: The Nannyarra Sandstone dips about 30°W and outcrops discontinuously along the eastern margin of the basin. It is transitional into the overlying Gneudna Formation by diminution of sand. The dominant lithology is fine-grained feldspathic arenite. There is a basal unit, 2 m thick, of silty sandstone below 3–4 m of clean, silicified, blockily bedded sandstone. This contains some trails and mudcracks. Large pits and scours are visible on extensive bedding plane exposures and imply deposition in the inner rough-zone of the shoreface. This is overlain by about 4 m of poorly exposed, thinly bedded silty sandstone, which marks the western side of the main sandstone ridge. On the flats west of the ridge, there are a few low strike ridges, each 1–2 m thick, of sparkling clean sandstone. Bedding plane exposures contain small wave ripples, parting lineations, possible adhesion surfaces, and some burrowing and trails. The formation as a whole was deposited in a beach environment (partly exposed and partly subaqueous) on an embayed coastline. Ephemeral beaches developed in coves, and there was bioturbation in sheltered areas.

The type section of the Gneudna Formation goes west from the Nannyarra Sandstone type section, over the south side of the broad hill of Gneudna Formation, to an elongate mesa of Munabia Sandstone just east of the main range of Munabia Sandstone. The formation consists of interbedded, hard limestone shoals and calcareous siltstone to argillaceous limestone. Regularly spaced limestone shoals impart a characteristic ‘train track’ appearance to outcrops.

There are faunal changes through the section. The lower 100 m of the section is only sparsely fossiliferous. Fossils are prolific above this and spiriferid brachiopods and orthoconic nautiloids are dominant for about two-thirds of the type section. Then rhynchonellid brachiopods become abundant, in medium- to thick-bedded, medium- to coarse-grained calcarenite. Corals and stromatoporoids are abundant in fine-grained calcarenites for most of the remainder of the type section. The uppermost 100 m is relatively unfossiliferous. The contact with the Munabia Sandstone is transitional over about 20 m stratigraphic thickness; hard calcareous beds decrease, siltstone increases, and thin sandstone intercalations increase and thicken.

GSWA Gneudna 1 was drilled in the claypan just west of the type section and encountered 358 m of Gneudna Formation and 101 m of Nannyarra Sandstone before being terminated in granitic basement. These thicknesses are approximately 100 m less and 50 m more than in the adjacent respective type sections. The former discrepancy was explained by an easterly dipping normal fault, whereas the latter corresponds in part to the covered interval between the two units (Mory, 1996b), and in part to topography on the basal unconformity, as the Nannyarra Formation is quite variable in thickness.

Locality 7: Munabia Sandstone and Willaraddie Formation, west of Gneudna Formation type section

Location: Immediately west of the Gneudna Formation type section, and then around the north end of the range.

Access: As for the Gneudna Formation type section. From the top of the Gneudna Formation type section, a track goes to the north end of the Munabia Sandstone ridge, along the eastern side. It may be necessary to drive cross-country south along the western side of the ridge to reach a reasonable outcrop of Willaraddie Formation.

Time: From the top of the Gneudna Formation type section, about 90 minutes return trip, including geology.

Notes: Advise either Moogooree or Williambury Homestead before entry. This section is logically done at the same time as the preceding section.

Geology: The Munabia Sandstone above the Gneudna Formation type section consists of a repetitive series of clean, well-sorted sandstone intervals, each separated by silty intervals. Tracks and bioturbation are present throughout the section, but are not common. Good bedding plane exposures of vertical burrows and trails are present at the northern end of the isolated hill at the bottom of the section. Bedding is mostly trough and planar cross-bedding, although swash cross-stratification is present locally. Contorted bedding is common and may have originated by overpressuring of dry sands by water and subsequent air expulsion. It is well exposed near the top of the isolated hill at the bottom of the section, on the eastern side. The section is interpreted here to be a barrier complex, in which the sandstone intervals are beach sands, and the siltstone intervals are back-barrier lagoonal deposits. Note that this interpretation differs from that presented by Hocking et al. (1987). There are thin dolomite horizons at the north end of the ridge; they contain a restricted conodont fauna and could be a lagoonal deposit or a protected, low-energy, nearshore-marine deposit.

Pebble and cobble conglomerate (the lowermost Willaraddie Formation) is exposed on the western side of the range. This overlies beach or nearshore deposits of the Munabia Sandstone and indicates that the lower Willaraddie Formation was deposited as a fan delta rather than an alluvial fan. The remainder of the Willaraddie Formation is not exposed in this immediate area.

Locality 8: Moogooree Limestone, Moogooree Homestead

Location: 1 km northeast of Moogooree Homestead, on the south side of the road to Mount Sandiman (see Fig. 1).

Access: Drive across the creek east of Moogooree Homestead on the road to Mount Sandiman. Continue about 1 km to where the road cuts through the Moogooree Limestone.

Time: 30 minutes to 1 hour.

Geology: This section is very close to the section shown by Hocking et al. (1987, figure 40) and is reproduced here (Fig. 11). It is dominated by algal dolomite. Dedolomitization is common in pipes and fractures in the upper part of the section (Hocking et al., 1987).

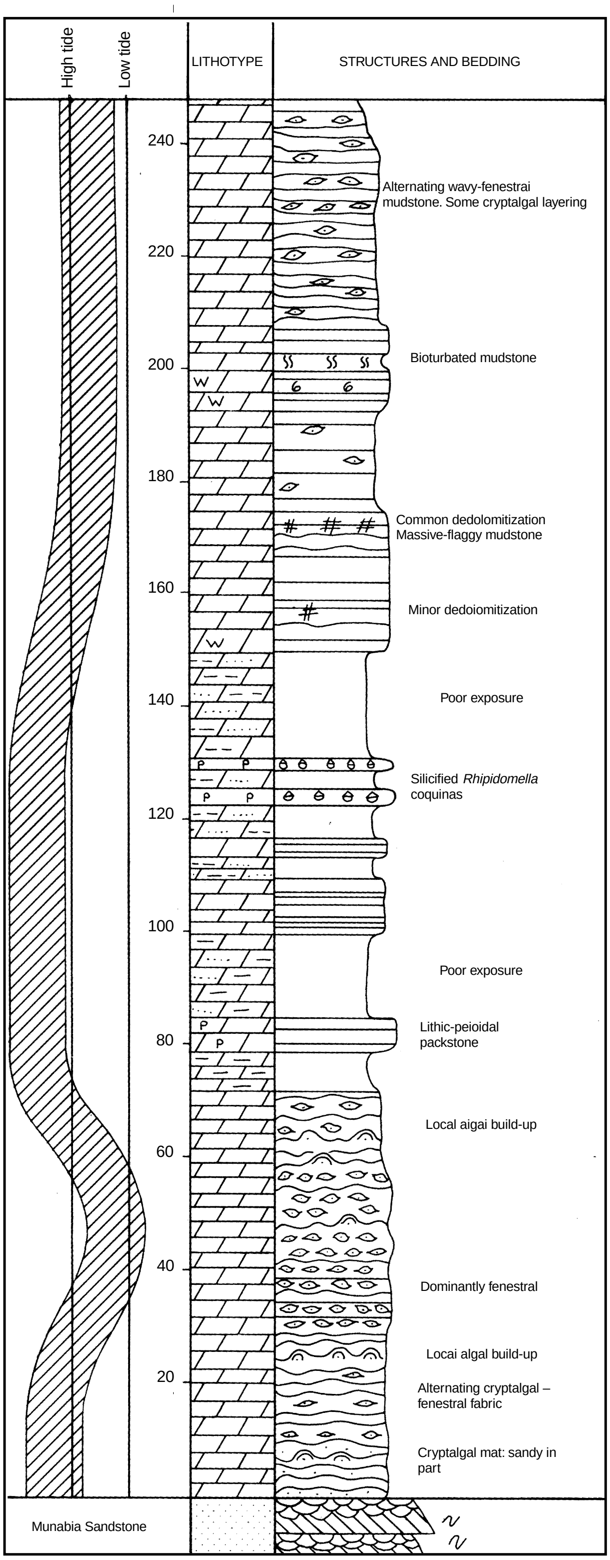


Figure 11. Moogooree Limestone, immediately east of Moogooree Homestead. From Hocking et al. (1987, fig. 40)

Eastern Carnarvon Basin: Upper Carboniferous and Permian

Background geology

The Upper Carboniferous – Permian succession contains two subunits that are separated by an abrupt early Artinskian boundary. The first subunit (Lyons Group, Callytharra and Cordalia Formations) is characterized by glacially influenced deposition and is up to about 3000 m thick. The second subunit (Wooramel, Byro, and Kennedy Groups) is dominated by silty and sandy, siliciclastic sedimentary rocks and has a cumulative thickness of 2900 m. Deposition extended from the Asselian (Late Carboniferous) to the Kazanian–Tatarian (Late Permian; Mory and Backhouse, 1997).

Lyons Group and Callytharra Formation: The Lyons Group contains a wide range of siliciclastic lithofacies and was deposited primarily on a marine shelf with a floating ice sheet, during the Late Palaeozoic, continental-scale glaciation of Gondwana. Coastal and continental deposition were present in the eastern Carnarvon Basin, and deposition spanned several glacial maxima and minima. The basin had onlapping margins and locally high topographic relief near the basin margin because of glacial sculpting. The basin margin may have been near the present-day margin, although pockets of deposition extended far onto Precambrian shield areas. Cold climatic conditions can be inferred from the low-diversity fauna (Dickins, 1979). Two formations are recognized within the group, a discontinuous basal sandstone (Harris Sandstone) and an upper calcareous siltstone (Carrandibby Formation). The latter is transitional into the overlying Callytharra Formation. The central part of the group is undivided.

The overlying Callytharra Formation is highly fossiliferous and carbonate dominated. Both the Callytharra and Carrandibby Formations were deposited primarily on a low-energy marine shelf at moderate depth, and both reflect the gradual melting of the ice sheet. The Callytharra Formation formed in the wake of post-glacial, eustatic sea-level rise, when warmer water temperatures caused carbonate deposition to increase. A significant episode of sandy deposition within the Callytharra Formation, the Ballythanna Member, was recognized in the Byro Sub-basin by Mory (1996a), and towards the north of the outcrop belt, the upper part of the Callytharra Formation grades into the Cordalia Formation. The latter unit is sandy in outcrop but in the subsurface is a micaceous siltstone devoid of macrofauna, to which Mory and Backhouse (1997) ascribed a prodeltaic environment of deposition.

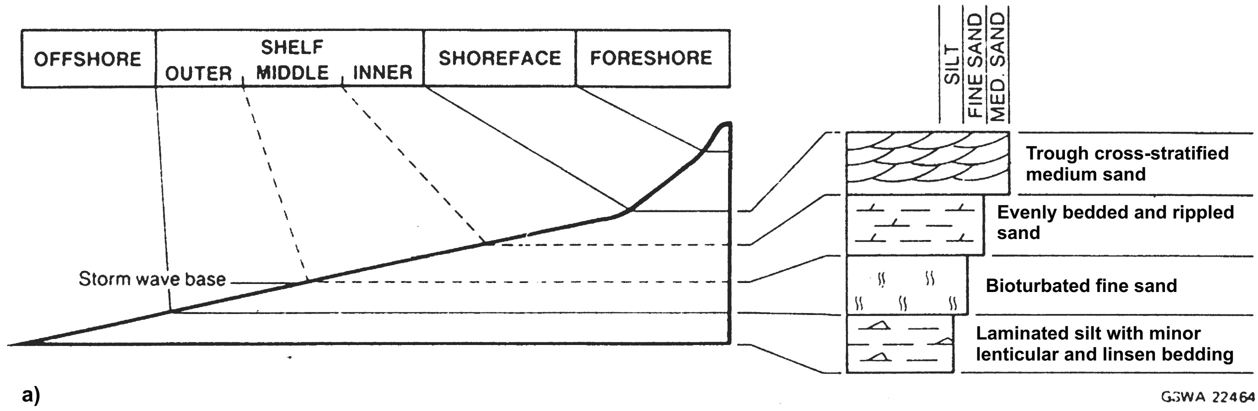
Wooramel, Byro, and Kennedy Groups: These are dominantly sandy or shaly units of Early to Late Permian age that contain only minor carbonate intercalations. The Artinskian Wooramel Group is sandstone dominated but has locally thick, siltstone and limestone intervals. The overlying Kungurian Byro Group is dominated by siltstone and shale; deposition alternated between shale and interbedded siltstone and fine sandstone. The Kennedy Group is similar to, but sandier than, the Byro Group. The upper two formations of the Kennedy Group are only sparsely fossiliferous and contain Ufimian (Late Permian) palynomorphs.

The Wooramel Group formed in fluviodeltaic and shallow-marine environments in the Artinskian. If there is a break with the underlying Callytharra and Cordalia Formations, it is too small to resolve on the presently available palynological zonation, although some break is still implied by the magnitude of the karstified surface on the top of the Callytharra Formation in the southern Merlinleigh Sub-basin (see Locality 14). Deltaic progradation was probably caused by isostatic rebound of the continental land-mass after the Asselian–Sakmarian ice sheet melted. Initially, a deltaic complex (Moogooloo Sandstone) prograded northwestwards over older units. This complex was flooded, and low-energy marine conditions (the lower part of the Billidee Formation) were established. A second phase of delta building resulted in several smaller deltas (within the upper Billidee and Keogh Formations). At the end of Artinskian, the rate of subsidence increased, and rapid deposition in somewhat deeper water conditions (Byro Group) ensued.

The Byro Group was deposited during the Kungurian on a storm-influenced, marine shelf (Moore et al., 1980a; Moore and Hocking, 1983; Fig. 12b). At this time there was a significant hiatus on the Peedamullah Shelf and Candace Terrace of the Northern Carnarvon Basin (Mory and Backhouse, 1997).

The basin stabilized during deposition of the uppermost Byro Group, and an increase in sand supply initiated deposition of the Kennedy Group (Fig. 12a). Storms were still active during deposition of the lower half of the Coolkilya Sandstone, but there are no indications of storm activity in higher sedimentary rocks of the Kennedy Group (Moore et al., 1980b). The upper Coolkilya Sandstone and Mungadan Sandstone were deposited on a broad, sandy marine shelf, primarily in shoreface and wave-swept shelf settings. The overlying Binthalya Formation formed in typically quieter conditions at greater depths, and choking of the basin may have begun at this time. In the Merlinleigh Sub-basin, the upper surface of the Kennedy Group is an eroded surface, so it is not known with certainty when deposition ceased. However, the low level of maturity of the Binthalya Formation (0.43% Ro near Birdrong Spring) suggests that deposition was negligible subsequent to the Kungurian, at least in that area (Iasky et al, 1998). In the Northern Carnarvon Basin, deposition of the Kennedy Group continued to the end of the Permian.

The basin geometry during deposition of the Wooramel, Byro, and Kennedy Groups appears to have been similar to that for the Lyons Group. There was syndepositional faulting in parts of the eastern part of the Southern Carnarvon Basin and Northern Carnarvon Basin during deposition of the Wooramel Group and Kennedy Group, but this appears to have been intrabasinal and did not change its gross geometry. The first stage of the evolution of the Carnarvon Basin ceased in the Late Permian, when the Palaeozoic depocentres became inactive. The fault-related deposition in the Northern Carnarvon Basin (Delfos and Dedman, 1988; Bentley, 1988) reflects the first deposition related to the Mesozoic sub-basins.



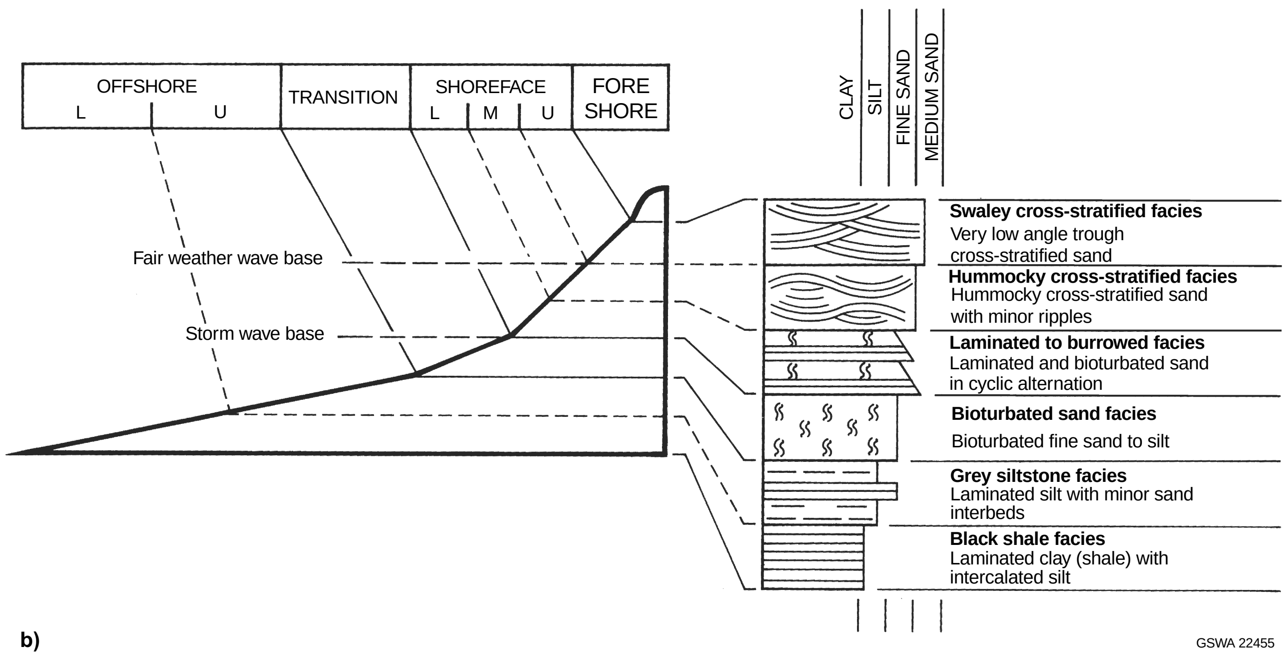


Figure 12. Depositional models for the Byro and Kennedy Groups (from Hocking et al., 1987, figs 61 and 70): (a) depositional model showing lithofacies and interpreted environments for the Kennedy Group, excluding the lower Coolkilya Sandstone; (b) depositional model showing lithofacies and interpreted 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

Locality 9: Gravity slumping, Harris Sandstone, Williambury Homestead

Location: 1.25 km east of Williambury Homestead; 23°51'45"S, 115°08'45"E.

Access: Park at Williambury Homestead, or cross the river on the Mount Sandiman road, turn left, drive east (four-wheel drive, dual range needed) along the south bank about 400 m to a fence and park where convenient. Walk upstream 600 m along the south bank. The slumping extends about 200 m along the southern bank, the full width of the sandstone ridge.

Time: 1 hour to 90 minutes, including walk.

Notes: Advise Williambury Homestead.

Geology: A wide ridge of Harris Sandstone extends from south of the Minilya River, to north behind Williambury Homestead. It is fault bounded (against Precambrian) on the west, overlies the Lower Carboniferous succession to the east, and dips about 20°W. There is fault repetition within the ridge, but the Harris Sandstone is still very thick compared to most other areas. It appears to be a nearshore marine deposit. The cause of the slumping is a massive sandstone unit between two siltstone horizons. Fluidization of the sandstone led to collapse of the upper siltstone as the sand flowed and dewatered, and slumping and contortion of the siltstone–sandstone sequence occurred. The fluidization may have been triggered by uneven sediment loading, ice loading, or an abrupt shock, such as an earthquake.

Locality 10: Lepidodendroid impression, Harris Sandstone, Williambury

Location: 3.75 km west of Williambury, on old telegraph line and access road; 23°51'45"S, 115°06'40"E.

Access: Four-wheel drive. Follow fenceline and old telegraph line west from Williambury Homestead, bearing 280°, for 3.7 km. This route is the old access road to the homestead, but it is now largely washed out. A low line of northerly trending sandstone ridges (Harris Sandstone) should be immediately to the west. Alternative access is from a track that runs south along the Williambury and Yindagindy Formations from a point about 500 m southwest of the turn-off to Williambury on the Lyndon–Middalya road. Drive southwest from the Williambury turn-off to the first grid, cross it, and drive east about 100 m to the track. The locality is about 3 km south, at the junction of the old access road to Williambury.

Time: About 20 minutes drive, one way; 15 minutes inspecting wood impressions.

Notes: Advise Williambury Homestead.

Geology: In this area, the Harris Sandstone consists of a series of discontinuous lenses of silicified sandstone between the Yindagindy Formation and undifferentiated Lyons Group. A glacial boulder bed underlies Harris Sandstone about 1 km to the south, which indicates that deposition was related to a glacial setting. The sandstone lenses were deposited in a nearshore, wave-winnowed environment, and the source of supply was presumably sand carried in glacial meltwater. Wood impressions are common in the sandstone immediately north of the track. A 20 by 30 cm impression of a lepidodendroid trunk with pinnules attached at one end (Hocking et al., 1987, fig. 50), is present near the top of the ridge about 15 m north of the track. All wood pieces are flat lying, which indicates that they were transported.

Blocky slabs of limestone from the Yindagindy Formation are exposed 100 m east of the ridge of Harris Sandstone. The limestone is a light-grey calcilutite (micritic) and contains numerous algae-encrusted brachiopods. The encrusting algae is *Girvonella*.

Locality 11: Mineralization in basal Lyons Group, Mount Sandiman

Location: 5 km south of Mount Sandiman; 24°28'50"S, 115°23'20"E.

Access: Four-wheel drive desirable. About 100 m to 2 km east of road between Lyons River and Minnie Creek stations, 1 km northeast of Austin Creek crossing, where the road swings from east–west to north–south. The Austin Creek crossing is the only formed crossing and major creek between Lyons River and the Mount Sandiman turn-off. Costeans should be visible east of the fence.

Time: 20 minutes.

Geology: The only known vein-controlled base metal mineralization in the Carnarvon Basin is at the base of the Harris Sandstone, about 5 km south of Mount Sandiman Homestead. In this immediate area, there are several small half grabens that contain westerly dipping Harris Sandstone above Precambrian basement. The fault planes contain veins up to 1.5 m wide of barite with minor sphalerite and galena. Some veins have been excavated to form costeans up to 3 m deep; fresh exposure can be seen in the costeans. An old mine and drive is present in the easternmost ridge, about 2 km southeast of the bend in the road.

Locality 12: Large erratic in Lyons Group, South Branch Well

Location: 50 m east of the Williambury–Moogooree road, 100 m north of the South Branch crossing (see Fig. 1).

Access: Accessible by two-wheel drive from the Williambury direction, assuming North Branch crossing at Williambury is passable. Four-wheel drive would probably be needed from the Mount Sandiman direction.

Time: 15 minutes drive south of Williambury.

Geology: A 100 m north of the river crossing, west of the road, there is an outcrop of Lyons Group, which includes a 2 m-high, broken granite boulder. Several other rock types are also present as smaller boulders in the immediate area. The size of the granite boulder and the variety of other rock types indicate a glacial, ice-rafted origin.

Locality 13: Glacial striae, graded bedding, and boulder beds, Weedarra Inlier area, Lyons River Station

Location: West and north sides of Weedarra Inlier, Lyons River Station. Basal pavement: 24°37'30"S, 115°24'40"E. Graded bedding: 24°36'S, 115°24'10"E. Soft-sediment striae: 24°41'00"S, 115°24'40"E, 150 m east of Alison Well.

Access: Four-wheel drive, dual range necessary. Off track from Lyons River Homestead to Deathtrap Outcamp, about 9 km drive east of the homestead. Alison Well is about 6 km south of the track to Deathtrap Outcamp, past 4 Mile Well.

Time: 15 to 20 minutes drive from Lyons River Homestead, one way, to the western side of the inlier. An additional 10–15 minutes cross-country to reach the graded bedding locality. About 1 hour round trip from track to see soft-sediment striae at Alison Well.

Geology: A basal glacial pavement (Hocking et al., 1987, fig. 46) is present in a ridge of Harris Sandstone, at the base of the sandstone, on the western side of the inlier about 200 m south of the track. It cuts into Precambrian gneiss, covers about 3 m^2, and dips about 50°W. A moderately well-exposed boulder bed can be seen about 150 m west of the ridge, immediately above the Harris Sandstone.

About 2 km north of the track, on the northern side of the inlier, there are two low ridges of Harris Sandstone. These ridges contain excellent examples of repeated graded bedding, syndepositional microfaulting, and grain-flow deposition (Hocking et al., 1987, fig. 45). In the Weedarra Inlier area, the Harris Sandstone was deposited primarily as outwash deltas in glacial lakes.

Evidence of iceberg grounding within a glacial lake is present in a prominent hill of Harris Sandstone, due east of Alison Well on the western margin of the inlier. The hill consists of about 20 m of sandstone and silty tillite capped by sandstone. On the northwest side of the hill near the top, there are several striated surfaces within the sandstone (Hocking et al., 1987, figs 47 and 49). The sandstone intervals were deposited in distributary channels of a glacial outwash delta, and ice moved over and grounded on the sand prior to its consolidation. Just west of the well, a low rise contains contorted, finely bedded to laminated siltstone and fine-grained sandstone. Access to the area is from a track, which links 4 Mile Well, Alison Well, and Damper Bore, west of the inlier. The track traverses a low rise of a white Cainozoic lacustrine limestone, the Nadarra Formation, between 4 Mile Bore and Salt Springs Creek.

Locality 14: Karst features on Callytharra Formation, Congo Syncline

Location: South of Yinilia Well in the core of the Congo Syncline, Dairy Creek Station; 25°20'S, 115°42'E.

Access: Turn south off the Gascoyne Junction – Dairy Creek road on the track about 200 m past the Congo Creek crossing. This passes between low ferruginized rises of Billidee Formation just south of the road. Continue south on the track, over Congo Creek (1.3 km south of the road) and through a strainer gate just over the creek. About 4.7 km past the gate, turn east through a gap in the Moogooloo Sandstone ridge; a faint track may be present. The karst terrain is immediately beyond the Moogooloo Sandstone.

Time: 90 minutes return trip from the road.

Geology: The labyrinth tower-and-corridor karst terrain in the Callytharra Formation has been interpreted as predating deposition of the overlying Moogooloo Sandstone (Hocking et al., 1987; Hocking, 1990a). Hard calcarenite horizons of the upper Callytharra Formation were selectively dissolved along joint corridors up to 20 m wide. Moogooloo Sandstone now infills these corridors but it is uncertain whether this is a Permian or more recent development. Synclines in the sandstone infill are common, and limestone debris is rare. If the karst developed wholly prior to deposition of the sandstone, limestone debris should be present in the sandstone. However, some karst towers are 30 m high, which is hard to explain by post-depositional solution. Given this, the synclines could be interpreted as compactional features associated with lithification of silty horizons in the Moogooloo Sandstone. Apparent 'flowstone' in some cavities in the Callytharra Formation implies that some small caves were present. Similar tower and corridor karst is present in the Canning Basin where Grant Group is draped over Nullara Limestone, on the eastern Lennard Shelf.

Locality 15: Varves, Coordewandy

Location: 200 m east of the ruins of Coordewandy Homestead, in the south bank of Daurie Creek; 25°35'40"S, 115°58'20"E. The creek is signposted as Coordewandy Creek, although it is the headwaters of Daurie Creek.

Access: Two-wheel drive from the road between Gascoyne Junction and Mullewa. Park near the creek crossing and walk downstream (west), or continue about 100 m past the creek and turn west onto the track into the ruins (a cement slab).

Time: 30–40 minutes total.

Geology: Possible varves are present in the Lyons Group at Coordewandy, where gently westerly dipping laminated siltstone extends about 100 m along the south bank of Daurie Creek (Hocking et al., 1987, fig. 43). The siltstone consists of alternating light-green (coarse silt) and mid-green-grey (fine silt) layers, each from about 2 mm to 1 cm thick. The layers have not been measured or counted, and the cyclicity has not as yet been explained. They could be genuine varves or very regular, distal lacustrine turbidites. The exact stratigraphic position of the exposures within the Lyons Group cannot be determined because of faulting and the poor standard of exposure in the group as a whole.

Yellow-brown layers are present each 1.4 to 2 m through the succession, defining a coarse cyclicity. Each cycle contains about 100 individual couplets, and a fining-upwards trend (from thick to thin couplets) can be seen in some of the coarse cycles. There is no obvious explanation for the cyclicity. If the individual couplets are glacial varves, the cyclicity is about each 100 years, which fits no obvious pattern, even hundred-year-storms because of the internal fining-upwards within the cycles. Alternatively, the couplets may be a shorter term feature, such as tidal rhythmites. If so, they are extremely thick and regular.

Locality 16: Moogooloo Sandstone type area, Gooch Range

Location: Hill NMF 575, south end of Gooch Range, Middalya Station.

Access: From Middalya, drive over the Minilya River and turn north onto the track about 150 m past the river. Continue along the track to the east face of Gooch Range near Mongie 2 Bore. Turn west and drive cross-country as far as possible towards the second major gully in the face of the range. The type section is up the gully.

Time: About 30 minutes drive from Middalya Homestead.

Notes: Advise Middalya Homestead before entry and check on access.

Geology: The section is as shown by Hocking et al. (1987, fig. 56B) and reproduced here (Fig. 13). Hard calcarenite shoals of the upper Callytharra Formation are the lowermost exposures. These are overlain by the Cordalia Formation, a coarsening-upward unit of bioturbated, thin-bedded silty sandstone. This developed in a shallowing-upward (because of progradation) prodelta environment. Clean quartz sandstone of the Moogooloo Sandstone forms the main bluffs at the top of the range. In the Gooch Range area, the structures in the Moogooloo Sandstone indicate that it was deposited primarily along the delta front of a wave-dominated delta. There are both westwards (fluvial domination, progradation) and eastwards directed (wave reworking, aggradation) cross-beds, and bioturbation is common in the lower part of the section. The common contorted bedding in the upper part of the section could be either water escape, air escape (when dry sand is covered by water), or small-scale slumping at the delta front.

The Billidee Formation is exposed in the hill on the dip slope about 200 m west. As at Moogooloo Hill (Hocking et al., 1987, fig. 59B; Fig. 13), the lower part of the formation is a black shale. This is interpreted as an offshore, subwave-base deposit, which resulted when influx to the delta waned and the delta was drowned by transgression and compaction. Calcarenite shoals are present at the same level in the Jimba Syncline and south of Mount Sandiman Homestead; these record shallowing-upward episodes and support a marine, rather than delta plain, interpretation for the shale. Repeated coarsening-upwards cycles above the shale record renewed delta progradation, but on a smaller scale than the Cordalia Sandstone – Moogooloo Sandstone couplet.

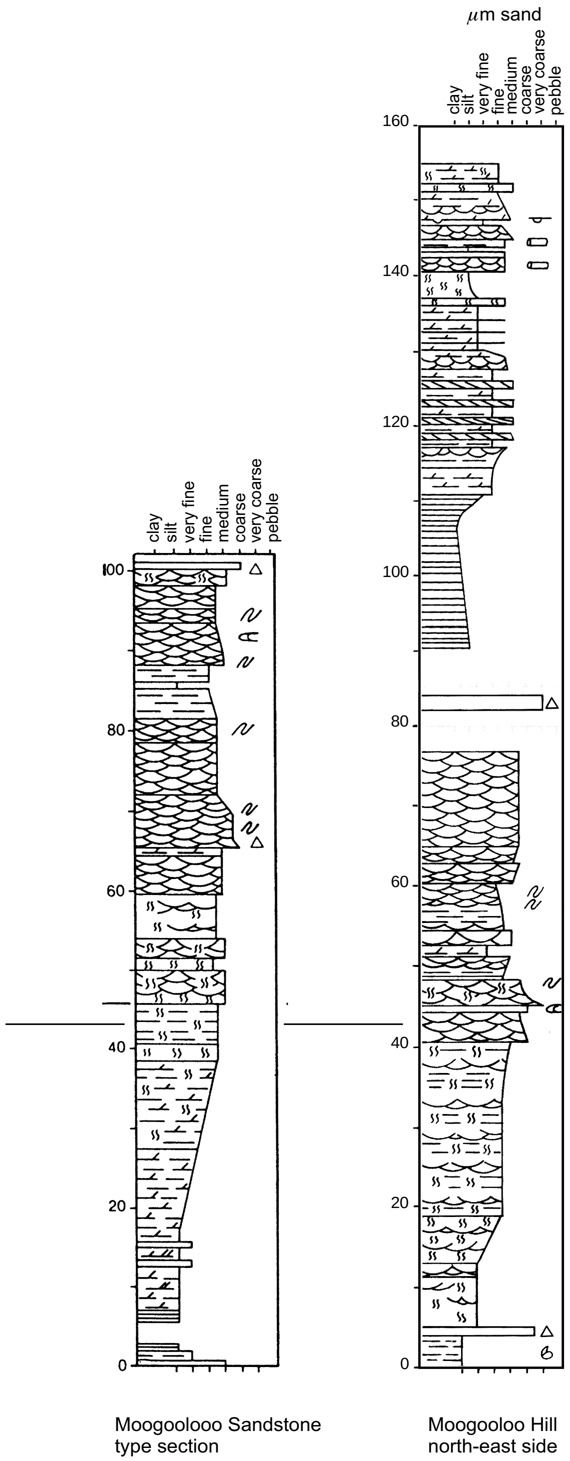


Figure 13. Measured sections of the Wooramel Group, southern Gooch Range. First exposure of Billidee Formation in Moogooloo Hill section is at 90 m. After Hocking et al. (1987, figs 56 and 59)

Locality 17: Permian succession, Toby Bore area, Moogooree

Location: West from Toby Bore, Moogooree Station (see Fig. 1).

Access: Drive 6.6 km southeast from Moogooree on the track to Toby Bore, past the rubbish tip. Continue past the bore, through the creek, and along the track to the first outcrops of Callytharra Formation.

Time: 2.5 hours return trip from Moogooree Homestead.

Notes: Advise Moogooree or Williambury Homestead before entry.

Geology: The section west from Toby Bore (Fig. 14) shows the upper Callytharra Formation in the northeastern Merlinleigh Sub-basin, a typical section of Moogooloo Sandstone, the type section of the Billidee Formation, and the lower part of the type section of the Coyrie Formation (Fig. 15). The sections through the Wooramel Group here and in the Gooch Range illustrate the degree of lateral change in the Wooramel Group.

The Callytharra Formation is similar to exposures in the Gooch Range. The lower part of the formation is a calcareous siltstone to silty micritic limestone with thin calcarenite interbeds. The hard calcarenite interbeds increase and thicken upwards, and are dominant in the upper part of the formation. The formation is a shallowing-upward succession.

The Cordalia Formation is absent along the east face of Kennedy Range. The Moogooloo Sandstone rests directly on the Callytharra Formation and is coarser grained and less sorted than in Gooch Range (Fig. 14). Bioturbation is present but less abundant than to the northwest. The cross-bedding is almost exclusively northwestward directed and fluvial dominated; the wave-dominated component is far less. The Billidee Formation is also coarser grained than in Gooch Range, but still has a shaly interval at the base (which is at a prominent, extensive bedding-plane exposure immediately east of a large, scree-covered ridge), and coarser grained intervals above. Deltaic, coarsening-upward sequences are not well developed in this section, but are present elsewhere along the eastern side of Kennedy Range. In the Toby Bore section, the Billidee Formation is thinner bedded and siltier overall than the Moogooloo Sandstone, and has relatively few cross-bedded intervals.

The lower Coyrie Formation (Fig. 15) is dominated by black shale and grey siltstone in this area, both of which formed as low-energy, offshore marine deposits. Some bioturbated sandstone and laminated to burrowed couplets are present near the base of the section. Several large boulders of varied rock types and typical glacial erratics of the Lyons Group are scattered around the floor of the valley, mostly adjacent to hills of Coyrie Formation. There are two possible interpretations. The first is that they indicate a minor glacial interlude in the Coyrie Formation, which is entirely possible since the Carnarvon Basin was located at about 70–80°S at this time, there are in situ erratics in the Billidee Formation at two other locations (Round Hill and Boonaberrie Bore), and the correlative Carynginia Formation in the northern Perth Basin contains in situ glacial erratics. The second is that the erratics were transported west from exposures of Lyons Group in the Eocene (when the Merlinleigh Sandstone was deposited) and settled to their present level.

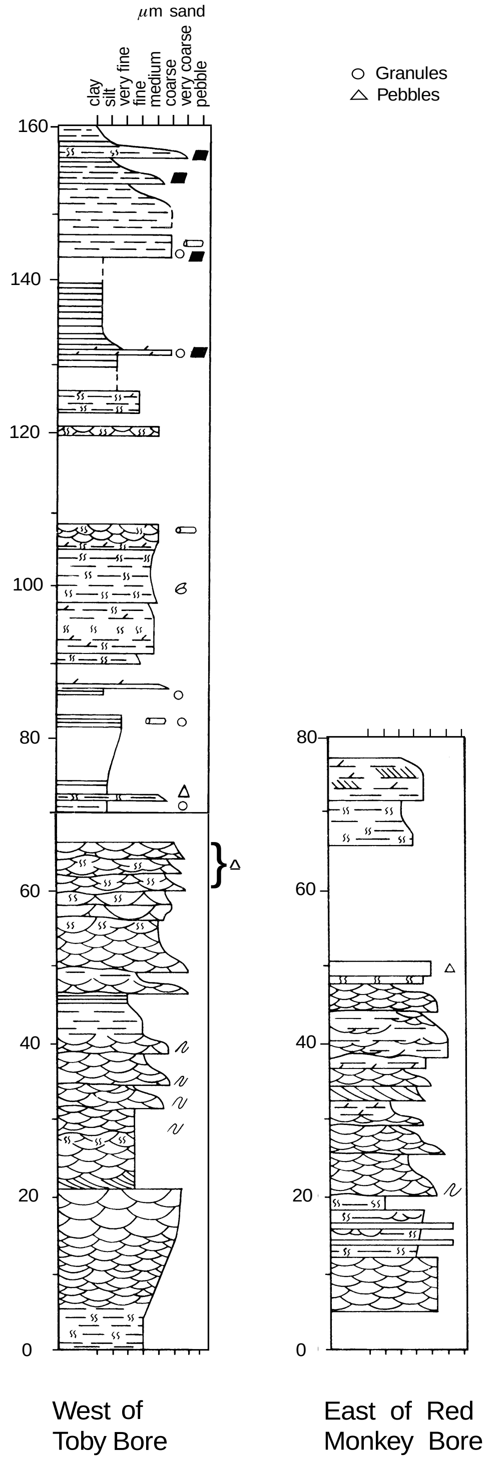


Figure 14. Measured sections of the Wooramel Group, Moogooree area. In the Toby Bore section, the Moogooloo Sandstone is 70 m thick and Billidee Formation is 90 m thick. After Hocking et al. (1987, figs 57 and 59). The upper 20 m of the section at Red Monkey could be better placed in the Billidee Formation

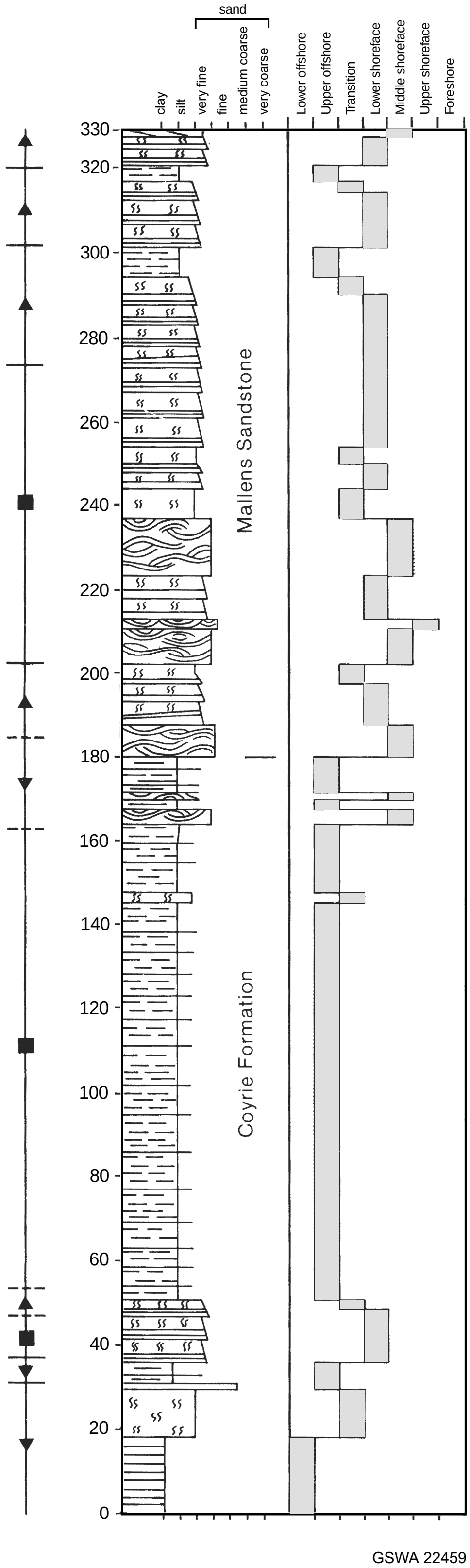


Figure 15. Type sections of the Coyrie Formation and Mallens Sandstone. From Hocking et al. (1987, fig. 65)

Locality 18: Mallens Sandstone type section, north end of Kennedy Range

Location: West of Red Monkey Bore, Moogooree.

Access: Four-wheel drive essential, dual range advisable. Either drive over the jump-up at the northwestern end of the valley west of Toby Bore, and then north to the Red Monkey tank – Donnelly Well track, or drive from Moogooree Homestead west to Red Monkey Bore, northwest to Red Monkey tank (along the pipeline), and west on the track to Donnelly Well. Turn south just past a major gully about 1.5 km west of Red Monkey tank, and drive cross-country to the point of the range near a prominent large fallen block.

Time: 45 minutes to 1 hour return drive from Moogooree, about 45 minutes for the geology.

Notes: Advise Moogooree or Williambury Homestead before entry.

Geology: The westerly dipping strike ridge at this locality is typical of the Mallens Sandstone. The lower part of the ridge consists primarily of hummocky and swaley cross-stratified sandstone (Fig. 15). This grades up into bioturbated sandstone and laminated to burrowed couplets (Fig. 15). A couple of eastward-directed cross-sets of coarse-grained sandstone near the top of the ridge could be small sand waves.

From the top of the ridge looking west, the succession is clearly cyclic, on an apparent 30–40 m scale, in that there are several strike ridges and valleys behind the main ridge. This cyclicity is not shown on the measured section of the type section, but the apparent scale of the cyclicity is similar to the alternation between hummocky cross-stratification and laminated to burrowed couplets.

Locality 19: Moogooloo Sandstone, Pells Range

Location: On the south side of the Gascoyne Junction – Dairy Creek road, 38 km east of Gascoyne Junction.

Access: Park beside the road and walk 50 m south to prominent breakaway of white sandstone.

Time: 30 minutes drive east from Gascoyne Junction, 30–45 minutes at the section.

Geology: The breakaway exposes an incomplete section of the upper Moogooloo Sandstone that is intermediate between the very proximal sections exposed in the eastern Byro Sub-basin (e.g. Bush Creek Syncline), and the distal sections exposed in the Gooch Range. The Moogooloo Sandstone here is dominantly coarse to very coarse grained sandstone, the product of deposition in a high-energy, fluvial-dominated distributary system in a low-relief delta. Marine influence is apparent in the minor bioturbation through the section, the bioturbated horizon at the top of the breakaway, scattered wave ripples, and winnowed, ?tidal channel, sandstone horizons. This indicates that the distributary system was located near the delta front in a subaqueous setting.

Locality 20: Wooramel Group and lower Byro Group, Geeranoo Creek

Location: Northern bank of Geeranoo Creek (previously known as Bush Creek), about 6 km north of the Gascoyne Junction – Mullewa road; 25°18'10"S, 115°56'50"E.

Access: Four-wheel drive advisable. About 11.5 km east of the Dairy Creek – Mount Augustus turn-off, there is a floodway (posted) on the road. About 300 m west of this, there is an old road branch to the north. A track branches north from this branch, along the western side of Geeranoo Creek. Follow the track or drive cross-country north-northwest, past the western side of a ferruginized ridge, to the prominent bluff of pale sandstone and siltstone on the northern side of Geeranoo Creek where it changes from a northwesterly to a westerly trend. Park on the south side of the creek.

Time: Approximately 15 minutes drive each way from the road, and 60–90 minutes at the section.

Notes: Advise Dairy Creek Homestead before entry, as a courtesy.

Geology: The Wooramel Group is exposed to the east of the main bluff in a separate fault block. It dips about 70ºW and is cut by numerous small faults. Both subhorizontal faults, which acted before tilting of the rocks, and high-angle faults, which developed after tilting, are present. The section is shown by Hocking et al. (1987, fig. 57A), although the extensive internal faulting means that the thicknesses shown are irrelevant — the section is a guide to gross lithofacies sequences only. The facies present are:

- flat-bedded quartz-pebble conglomerate. This has a matrix of coarse-grained, texturally and compositionally immature feldspathic wacke, and is interbedded with

- cross-bedded, medium- to coarse-grained clayey sandstone, in part with parasitic ripples, and
- laminated to rippled, non-bioturbated siltstone.

These form the lower two-thirds of the section, and are interpreted as sheet-flood conglomerate, channel-bar sandstone, and abandoned channel–overbank siltstone. The upper 15 m of the section is

- slightly ferruginized, very silty and clayey sandstone and siltstone, flat bedded with clay-draped interference ripples, and containing scattered trails on bedding planes and rippled surfaces. This is capped by about 5 m of
- coarse-grained, bioturbated, and cross-bedded brown sandstone.

This portion of the section is equivalent to the Billidee Formation, and is interpreted as a subaqueous delta-bay deposit.

The lower Byro Group is exposed in the large bluff and consists of proximal Coyrie Formation and (possibly) Mallens Sandstone. The transition into the Wooramel Group is not exposed. The lower 12 m consists of hummocky cross-stratified, laminated to burrowed, and bioturbated sandstone, and is interpreted as a storm-influenced shoreface to inner shelf sequence. A prominent ferruginized bed, 30 cm thick, separates this interval from the overlying 14 m of intensely bioturbated, cyclic sandstone and siltstone. The ferruginized bed marks a discontinuity and shift up into an interdistributary bay and crevasse splay setting. This portion of the section may correspond to the Mallens Sandstone.

Locality 21: Wooramel Group, Mulyajingle Peak area

Location: 1–2 km north of Mulyajingle Peak, eastern margin of Byro Plains. Approximately 26º09'45"S, 115º57'30"E.

Access: About 17 km along the Woodleigh road from the turn-off on the Gascoyne Junction – Mullewa road, on a northerly trending section, turn west onto the track to Boondie Well. Proceed about 2 km through the range, stopping as appropriate for the Moogooloo Sandstone. It is relatively easy cross-country driving north and south along the west side of the range, through the Keogh Formation.

Time: Allow 20 minutes each way from the Gascoyne Junction – Mullewa road, and about 90 minutes on the west side of the range.

Geology: The Moogooloo Sandstone is exposed along the eastern side of the low range of which Mulyajingle Peak is a part, and the Keogh Formation is exposed in breakaways along the west side. The exposures are not exceptional, but are the southernmost, easily accessible (from the Gascoyne Junction – Mullewa road) exposures of the Wooramel Group in the Carnarvon Basin.

The Moogooloo Sandstone in this area is dominated by very coarse grained arkosic sandstone to granule conglomerate. The sandstone is a texturally immature, feldspathic to lithic wacke in which quartz pebbles and granules are abundant. It is mostly trough and planar cross-bedded, and contorted bedding is present locally (Hocking et al., 1987, fig. 58). Palaeocurrents indicate westwards to northwestwards flow. It is interpreted as a moderate- to high-energy, braided-fluvial deposit. Possible marine influence is apparent from rare, vertical burrows at the very top of the Moogooloo Sandstone, north of the Boondie Well track.

A sharp flooding surface separates the Moogooloo Sandstone from the overlying Keogh Formation. There is an abrupt change to wavy-bedded sandstone and siltstone, and rippled siltstone to fine-grained sandstone. Cross-bedded, coarse-grained arkosic sandstone intervals are common, both as discontinuous, steep-sided, narrow scours and discontinuous to laterally extensive channels and sheets. These are well exposed in a southerly facing breakaway about 500 m north of the track, on the westernmost edge of the range. Quartz and chert boulders from 20 cm to 1 m in diameter are scattered throughout the unit and indicate alpine glacial influence. There is one large boulder on the north side of the nearest butte, south of the track. In the Mulyajingle Peak area, the Keogh Formation is interpreted as a interdistributary bay sequence. Crevasse splay floods and small channels crossed the bay, and the climate was subpolar, so that there was little vegetation or chemical breakdown of feldspar. Deltaic lobes and distributary systems are present elsewhere in the Byro Sub-basin.

Locality 22: Lower and middle Kennedy Group, east side of Kennedy Range

Location: Picnic area, east side of Kennedy Range.

Access: Two-wheel drive. Turn west onto a formed road leading to Kennedy Range, about 6.5 km south of Lyons River Homestead on the road to Gascoyne Junction.

Time: 2.5 hours from the turn-off, return trip.

Notes: Advise Lyons River Homestead if you drive an appreciable distance north or south of the obvious tourist area.

Geology: A good section of Coolkilya Sandstone and Mungadan Sandstone is exposed in the face of Kennedy Range, in and along the face of the spur just south of the carpark. Figure 16 shows a similar section about 5 km south of the picnic area. When you reach a large, undercut face and vertical bluff in the Coolkilya Sandstone, you will need to go around to, and maybe beyond, the point of the spur. The section near Range Bore (Fig. 16) is sufficiently similar that it can be used as a rough guide to the section.

The section of Coolkilya Sandstone at the picnic area consists primarily of greenish-grey, fine- to medium-grained silty sandstone (feldspathic to lithic wacke). At the base, the dominant facies is swaley cross-stratification, with lesser amounts of hummocky cross-stratification and hummocky to burrowed or laminated to burrowed couplets. This grades up into bioturbated sandstone and laminated to burrowed couplets. *Zoophycos* traces are abundant near the large undercut and vertical face.

The boundary between the Coolkilya and Mungadan Sandstones is marked by a pronounced colour change in the rocks. The Mungadan Sandstone is coarser grained than the Coolkilya Sandstone, and is dominated by bioturbated sandstone and thick, flat-bedded intervals. Some cross-bedded, channel-infill intervals are also present. The facies models proposed by Moore et al. (1980b) imply that the Mungadan Sandstone is, on the whole, a more distal deposit than the Coolkilya Sandstone, in that they considered hummocky and swaley cross-stratification to be shoreface deposits, and bioturbated and flat-bedded deposits to be shelf deposits, seaward of the shoreface.

The Mungadan Sandstone is best interpreted as a more proximal deposit than the underlying Coolkilya Sandstone. Deposition of the Byro Group and Coolkilya Sandstone was dominated by marine processes, in that there is little indication of continental influence. Storms, waves, and tidal currents reworked and distributed sediment that was brought into the basin. The overlying Mungadan Sandstone developed when that marine dominance ceased. When wave and tidal effects diminished, sands prograded into the basin to form (in the vicinity of Locality 22) a nearshore, fluvial-dominated, subaqueous channel-complex. Tectonic silling of the basin or limestone buildups to the northwest (e.g. Fennel 1, Hope Island 1) may have caused the decrease in marine influence.

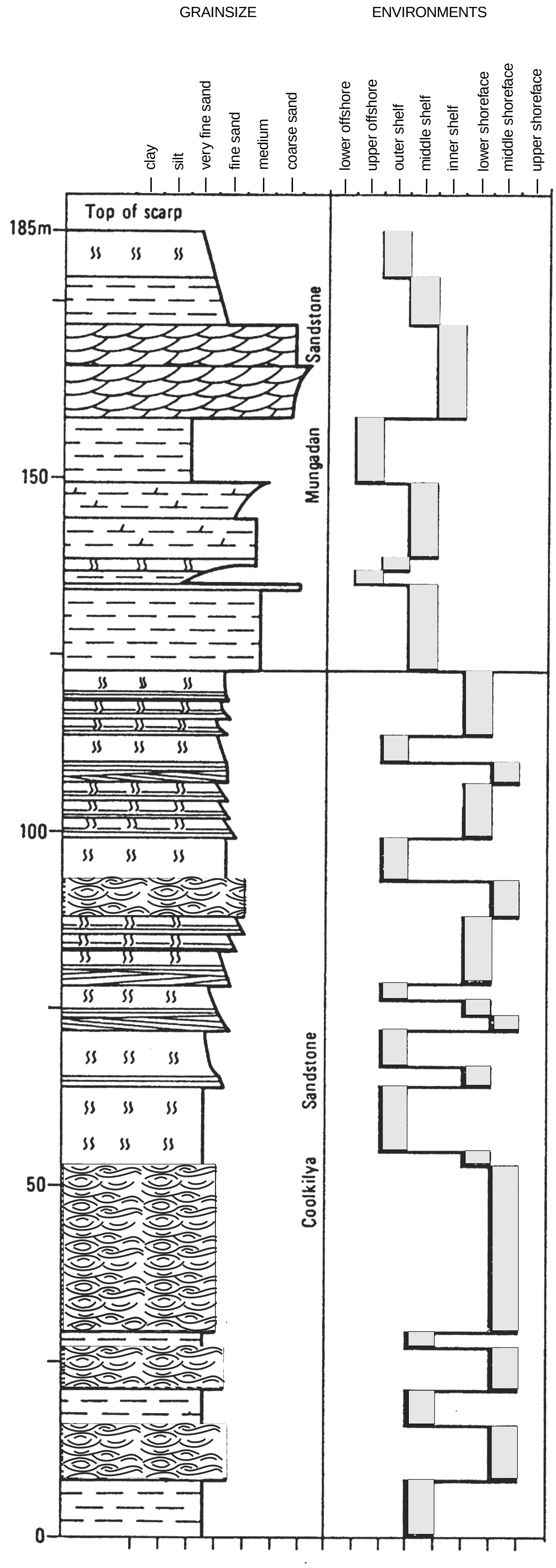


Figure 16. Measured section of the Coolkilya and Mungadan Sandstones, Range Bore, east side of Kennedy Range about 5 km south of the picnic area. Densely patterned troughs are hummocky and swaley cross-beds, open troughs are normal trough cross-beds. From Moore et al. (1980b, fig. 3)

Locality 23: Upper Byro Group and Kennedy Group, Wandagee Hill

Location: East face of Wandagee Hill, Wandagee Station.

Access: Two-wheel drive. From Wandagee Homestead, drive west along the road to Minilya roadhouse until the turn to the shearing sheds (enquire at homestead for distance). Drive south past the shearing sheds to the old main road, turn east. Drive east until just past Wandagee Hill, turn north and park on the southeast side of the hill.

Time: From the main road, about 90 minutes return trip.

Notes: Advise Wandagee Homestead before entry.

Geology: West of the shearing sheds, there is an old quarry that was used as road base for the access road to Quail 1. This contains relatively fresh exposures of Windalia Radiolarite.

About 100 m southeast of the hill, just north of the road, it may be possible to find some calcite veins and crystals in surface rubble. These mark the location of an immediately subcropping, alkali-picrite intrusive pipe. These pipes were the target of a concentrated, but unsuccessful exploration program for diamonds in the late 1970s.

The sedimentary succession in and near Wandagee Hill consists of the Nalbia Sandstone and Baker Formation (upper Byro Group), Coolkilya Sandstone, Mungadan Sandstone, and about 1 m of Binthalya Formation. The Nalbia Sandstone is relatively poorly exposed, but consists of medium-grained, pinkish sandstone in ridges around the base of the hill. Hummocky cross-stratification can be recognized locally. The Baker Formation is a grey siltstone that contains abundant trace fossils.

The Coolkilya Sandstone is shown in Figure 17. The lower half is dominated by laminated to burrowed couplets of fine- to medium-grained sandstone. These are overlain by bioturbated and flat-bedded sandstone in the upper part of the formation. The boundary between the Coolkilya and Mungadan Sandstones is at a broad ledge in the hill, and is marked by a colour change in the rocks. It consists of flat-bedded and bioturbated, medium-grained sandstone and is similar to the upper Coolkilya Sandstone. The Binthalya Formation is present only near the trig point and consists of a few metres of bioturbated sandstone and ferruginous rubble.

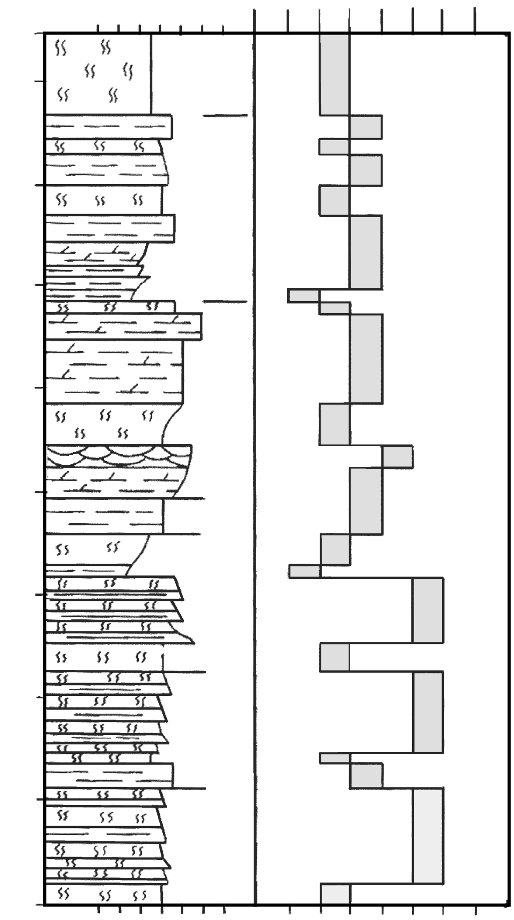


Figure 17. Type sections, Coolkilya and Mungadan Sandstones, Wandagee Hill. In the lower Coolkilya Sandstone, the outer shelf is equivalent to the transition zone. From Hocking et al. (1987, fig. 71)

Locality 24: Cundlego Formation, Cundlego Crossing

Location: Cundlego Crossing, Wandagee Station.

Access: Two-wheel drive. Drive about 8 km west from the Wandagee Homestead turn-off on the main Minilya–Middalya road to the second grid. The turn-off to Cundlego Crossing is just east of this grid, towards the north, and is a major station track. Drive about 2 km to the crossing at the Minilya River. Alternatively, the turn-off is about 45 km east of the highway.

Time: 30 minutes return trip from the main road.

Notes: Check access at Wandagee Homestead if desired.

Geology: Cundlego Crossing is in the central portion of the left-hand section in Figure 18. Excellent, laterally extensive exposures of swaley and hummocky cross-stratified sandstone are present in the Cundlego Formation at Cundlego Crossing. Transported, storm-concentrated coquinas are present within the swaley cross-stratified interval; these are localized pockets of shells and shelly fragments.

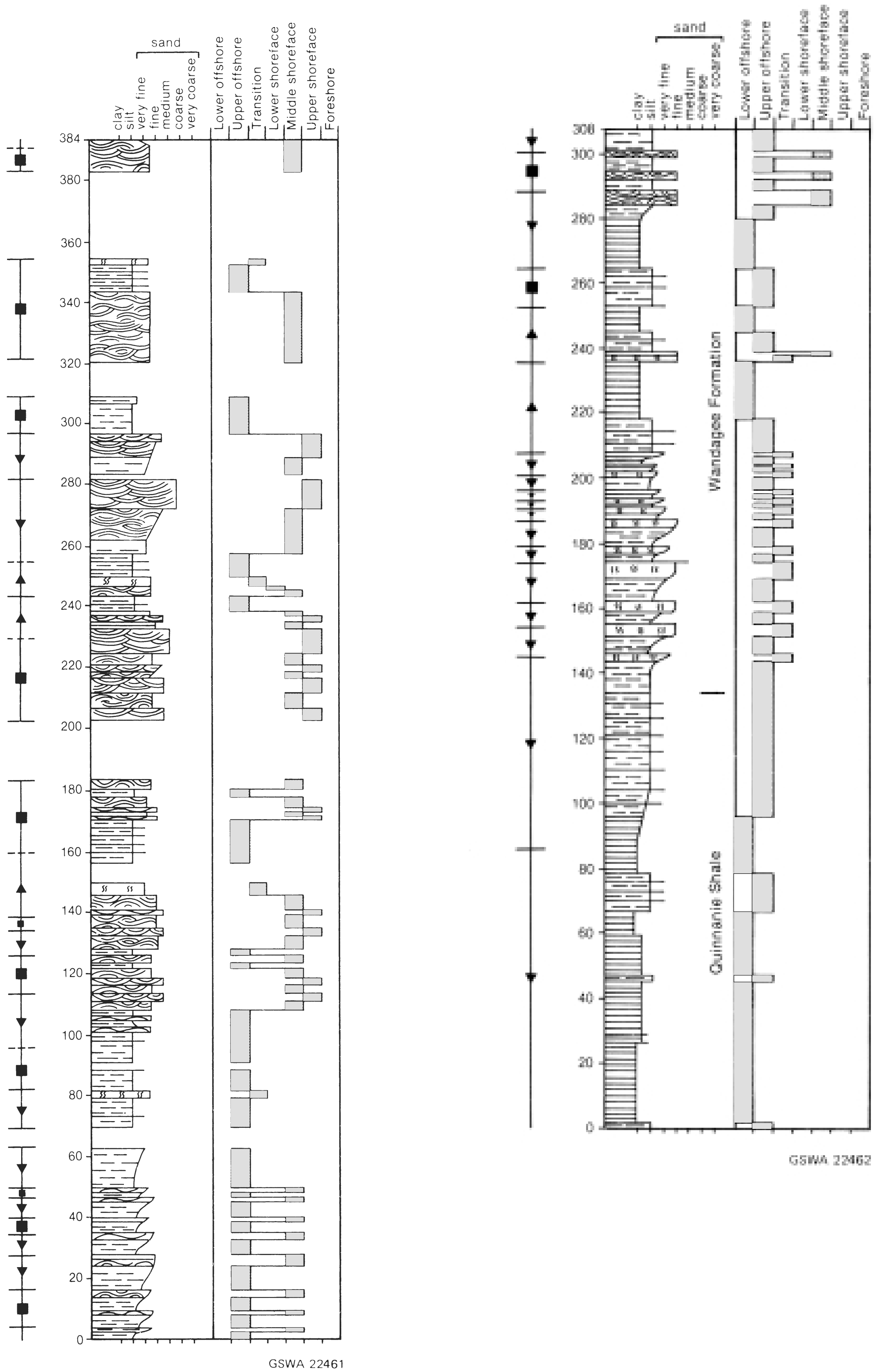


Figure 18. Measured section of the Cundlego Formation, near type section (left), and type section of the Quinnanie Shale and Wandagee Formation (right), Minilya River, Wandagee Station. From Hocking et al. (1987, figs 67 and 68)

Locality 25: Byro Group, Coolkilya Pool area

Location: Downstream from Coolkilya Pool, Wandagee Station.

Access: Drive 11.9 km west from the Wandagee turn-off on the Minilya–Middalya road. A strainer gate is present in a fence 300 m to the north. Follow a track through the gate north to the river, and then west about 150 m south of the river. The track finishes at a large ridge and bar of the uppermost Cundlego Formation. From Coolkilya Pool, walk downstream. Four-wheel drive is advisable but not essential.

Time: 1 hour to 90 minutes at the section.

Notes: Check access at Wandagee Homestead.

Geology: The type sections of the Wandagee Formation and the Quinnanie Shale (Fig. 18, right) extend west along the north bank of the Minilya River from near Coolkilya Pool. Coolkilya Pool itself is in the upper Cundlego Formation.

Excellent flooding surfaces and metre-scale parasequences are exposed in the upper Cundlego Formation and basal Quinnanie Shale. The Quinnanie Shale is poorly exposed and characterized by thin, sheet-like gypsum veins, derived from the oxidation of pyrite. Where fresh, it consists primarily of soft, black shale and dark-grey siltstone. The Wandagee Formation is dominated by very fossiliferous grey siltstone and, in the lower part of the formation, coarsening-upwards cycles from grey siltstone to fine-grained, bioturbated sandstone. Hummocky cross-stratification is present at the top of the unit, just below the transition to the Nalbia Sandstone. Many of the fossils in the unit form in storm-concentrated coquinas as local pockets of shells and shelly fragments.

Northwestern Kennedy Range: Cretaceous and Permian

Background geology

Permian: See **Background geology** in **Eastern Carnarvon Basin: Upper Carboniferous and Permian**.

Birdrong Sandstone: The Birdrong Sandstone is a massive sandstone that contains only minor siltstone or conglomerate. The sand is commonly relatively clean and moderately sorted, and locally glauconitic. Cementation is commonly minimal, both in outcrop and the subsurface. A very glauconitic interval is commonly present at the top of the unit around Kennedy Range. This was previously included in the Birdrong Sandstone, but is now considered to be part of the Mardie Greensand.

In outcrop, the Birdrong Sandstone contains four main lithofacies. Poorly sorted, cross-bedded sandstone and minor siltstone or claystone are present locally at the base of the formation, and contains westward to northward palaeocurrent directions. The facies is a fluvial channel-fill deposit, where the channels were primarily depressions in the indurated unconformity surface beneath the Birdrong Sandstone. Deposition may have been partly subaerial and partly subaqueous (coastally situated), as rare trace fossils are present. A large, incised siltstone cross-bed is present in the type section near the top of the facies (see below); it probably developed by the infilling of an abandoned channel. The basal facies is preserved only locally because of low sediment influx to the basin; an incoming transgression reworked all prior sediment, except in protected or pronounced topographic lows.

Bioturbated and cross-bedded, fine-grained sandstone, locally with interbedded sandstone and siltstone, constitutes most of the Birdrong Sandstone. Palaeocurrents were eastward, although data are scarce. The facies is interpreted as a shoreface to inner-shelf deposit.

Very low angle cross-bedded, very fine grained, texturally mature sandstone with scattered *Skolithos* forms a marker bed in the centre of the Birdrong Sandstone in most sections. The cross-bedding is the swash cross-stratification of Harms et al. (1982), and together with *Skolithos* indicates a foreshore or beach environment.

Bioturbated, variably glauconitic, horizontally bedded sandstone and bioturbated, lenticular- to flaser-bedded sandstone and siltstone form at the top of the Birdrong Sandstone in some sections. Bioturbation varies from common to intense, and glauconite is common. Laterally, this facies grades into the Mardie Greensand. It developed primarily in the lower shoreface zone, where deposition is slow, sand dominated, and not subject to constant wave reworking. Lenticular bedded intervals may have formed in adjacent deeper conditions on a marine shelf slightly below wave base.

The Birdrong Sandstone is a transgressive sand body. The poorly sorted sandstone facies is either a fluvial lowstand deposit directly related to the interval above it, or a pre-existing fluvial deposit that could be equivalent to the lower four units in the Nanutarra Formation or even older. The base of the main section records removal of all coastal deposits, so that deposition began in lower shoreface or shelf conditions (Fig. 19) when the bioturbated and cross-bedded sandstone facies was deposited as a transgressive system tract. In most areas, progradation occurred as the transgression slowed, and the swash cross-stratified facies was deposited in foreshore conditions as a highstand system tract. Renewed transgression, with no marked regression of sea level, led to deposition of more of the bioturbated and cross-bedded facies, and then the bioturbated glauconitic facies or Mardie Greensand. These can be regarded as a combined shelf-margin systems tract and transgressive systems tract deposit.

Mardie Greensand: The Mardie Greensand is recognized simply as a greensand-dominated unit, where a greensand is defined as a sandstone that has a glauconite content of greater than 35%. In most areas of outcrop, the glauconite has been weathered to ferruginous minerals and recognition of the unit depends on a combination of features: recognition of weathered glauconite, intense bioturbation, and planar to wavy bedding.

In outcrop, the only facies that has been recognized in the Mardie Greensand is an intensely bioturbated greensand to highly glauconitic sandstone. The bioturbation has commonly obliterated original bedding and imparted a massive appearance. Where bedding remains, it indicates that the sediment was originally wavy bedded to flaser bedded.

The Mardie Greensand was deposited, and evolved, on a shallow, moderate- to low-energy, marine shelf (Fig. 19). Terrigenous influx was low (in that the area of deposition lay shoreward of the zone of mud deposition, but seaward of the main zone of sand deposition), the bottom was wave swept or current swept, and biogenic activity was intense. The shelf was shallower than for most of the Mardie Greensand as some outcrops are near the basin margin, where subsidence has been minimal since the Cretaceous. Thin-section examination indicates that much of the glauconite is in situ, rather than transported from deeper, offshore areas such as the Barrow Sub-basin.

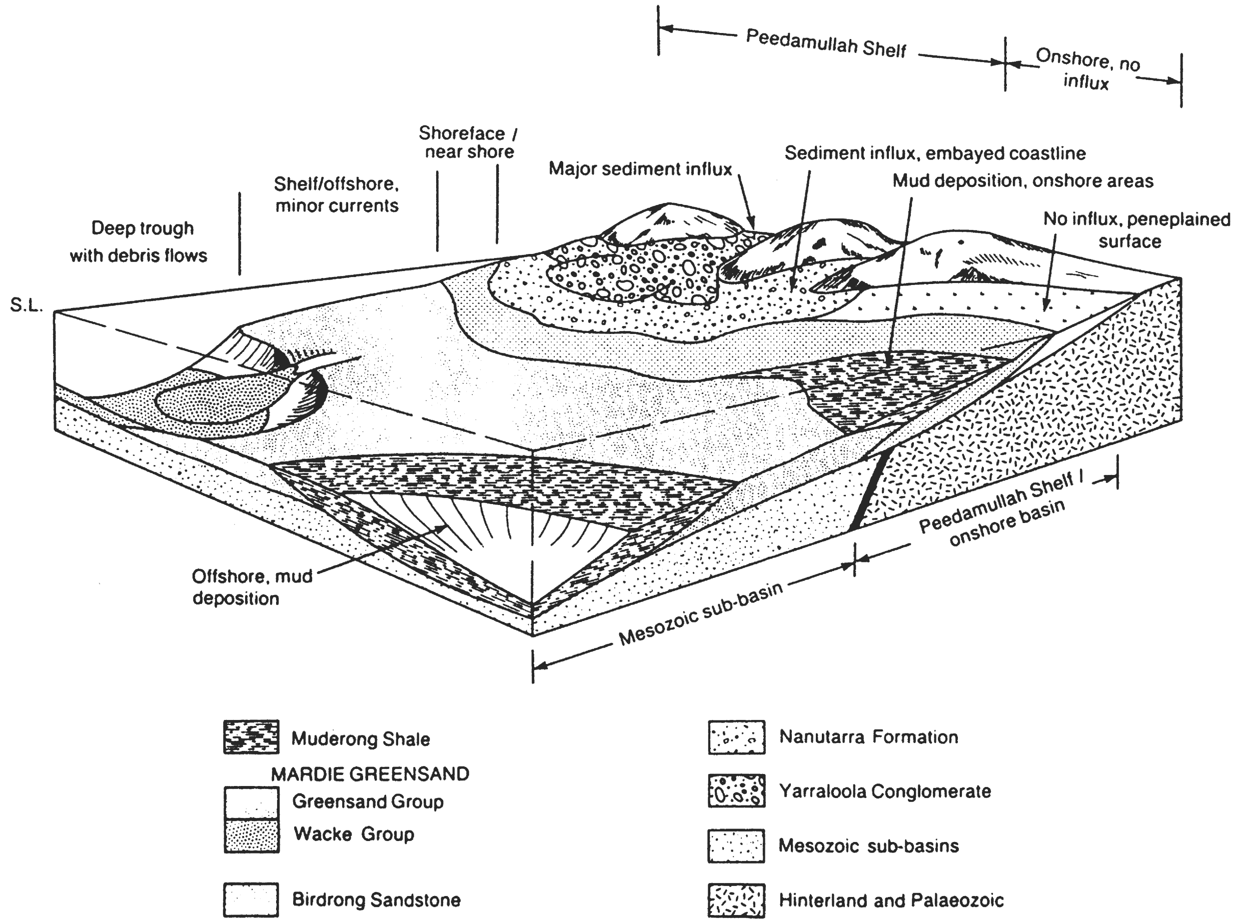


Figure 19. Depositional model for sandy units at the base of the Winning Group. The wacke group of the Mardie Greensand is not recognized in outcrop. After Hocking et al. (1988, fig. 18)

Locality 26: Muderong Shale type area, Twin Bores, Middalya

Location: 2.5 km southwest of Twin Bores, Middalya (see Fig. 1). The type section is a northerly facing breakaway in the westernmost high butte of Cretaceous sedimentary rocks.

Access: Four-wheel drive, dual range essential. Turn south opposite Middalya Homestead from Minilya–Williambury road, and follow the main graded track for about 20 km to hills just north of Paddys Outcamp. Turn east onto a seismic line now used as the track, then south after about 3 km onto another seismic line to a fence, mill, and tank. Follow the fence and pipeline for about 6 km, past Hill Tank to Twin Bores. Cross the small creek just beyond the bores, turn right (southwest), and follow the track along the fence for about 2 km to a saddle. The type section is about 500 m to the west. It is possible to drive all the way to the type section, but the country is rugged and it may be quicker to walk the last kilometre.

Time: From Middalya, allow 6 hours for a return trip if you also visit the fault drag locality.

Notes: Advise Middalya Homestead before entry.

Geology: The type section of the Muderong Shale (Fig. 20) is in a northerly facing breakaway at the head of a northerly draining gully. The Mardie Greensand and upper part of the Birdrong Sandstone are exposed immediately below the Muderong Shale (Fig. 20). The contact between the Mardie Greensand and Birdrong Sandstone is just above a well-exposed, bedding-plane surface of *Diplocraterion* ‘yoyo’ burrows. The lower boundary of the Muderong Shale is just above a prominent ledge, but is not distinct.

The lower Birdrong Sandstone is exposed 150 m to the east in a low breakaway. The contact with the underlying Coolkilya Sandstone is difficult to pick because of poor exposure and similar lithofacies, but bioturbated, subwave-base sandstone and swash cross-stratified, foreshore sandstone are well exposed.

The Windalia Sand Member may be present at the top of the Muderong Shale as a very fine grained, light-yellow sandstone immediately below the white, blockily bedded Windalia Radiolarite (Fig. 20). The yellow beds can also be regarded as impure Windalia Radiolarite. The Windalia Radiolarite itself constitutes the remainder of the hill, and is typical of the radiolarite in the Kennedy Range area. It has a characteristically low mass and is very porous (indicated by the manner in which it sticks to the tongue). This is in large part because of the very porous nature of the radiolarians.

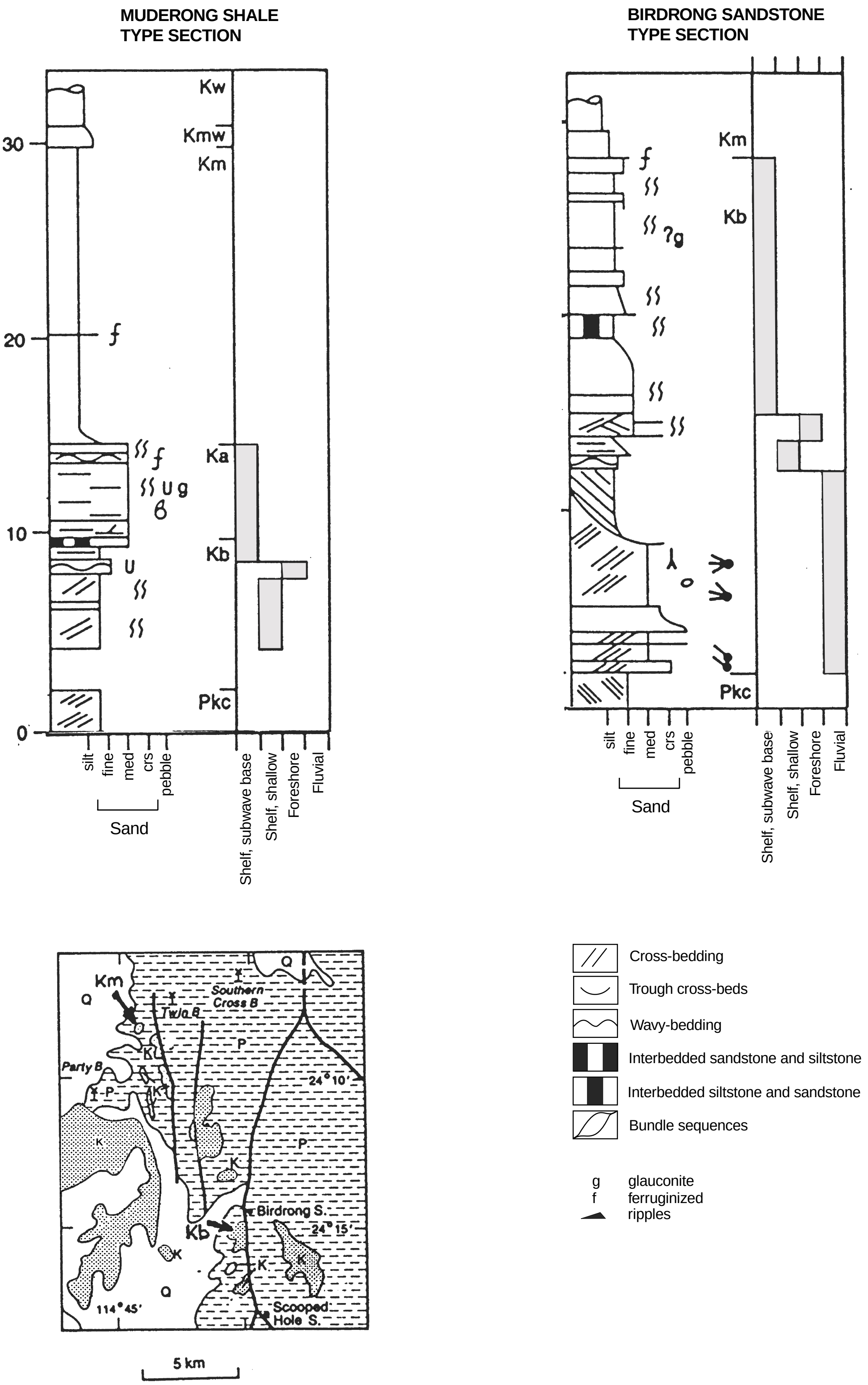


Figure 20. Type localities, Muderong Shale (left) and Birdrong Sandstone (right), northwestern Kennedy Range, Middalya and Mardathuna stations. Locations of sections are shown by arrows on the map. Symbols and patterns are common through Figures 20 to 28. *Pkc*: Coolkilya Sandstone. *Kb*: Birdrong Sandstone. *Ka*: Mardie Greensand. *Km*: Muderong Shale. *Kmw*: ?Windalia Sand Member. *Kn*: Windalia Radiolarite

Locality 27: Baker Formation, Hill Tank, Middalya

Location: In the hills around Hill Tank, Middalya. This is simply a convenient area to see the uppermost Byro Group, en route to the Muderong Shale type area.

Access: As for Muderong Shale type area. Stop as appropriate on the track between Paddys Outcamp and Twin Bores, near Hill Tank.

Time: 15 minutes.

Geology: Most of the hills around Hill Tank consist of Baker Formation. The basal Coolkilya Sandstone caps the hills. The Baker Formation consists mostly of bioturbated, very fine grained sandstone and siltstone, whereas the Coolkilya Sandstone is a lighter coloured, fine- to medium-grained sandstone.

Locality 28: Drag faulting, Twin Bores, Middalya

Location: A southerly facing notch on the south side of the northernmost Cretaceous mesa on the Middalya Fault.

Access: As for Muderong Shale type section. Park along the fence where convenient just west of the Middalya Fault (this is relatively easy to pick because of structural dips and discontinuities), walk about 1 km south and climb over the saddle. A steeply dipping (45°) section of Windalia Radiolarite is immediately to the west. The best view is from the mesa about 300 m south.

Time: 20–25 minutes walk and climb from the track, one way. About 30 minutes to walk around the locality.

Geology: The major movement on the Middalya Fault was in the Triassic to Jurassic and is down to the east; this is the sense of displacement on the Permian rocks. Later reverse movement (down to the west) affected the Cretaceous to give the present structural setting. The net result is that the Cretaceous Winning Group in the west block abuts Permian Kennedy Group in the east block.

In the western block, the Cretaceous rocks dip west at about 45°. Immediately west of the fault, the dip decreases and they roll over to a dip of 5–10°E. This is seen in the central, north–south ridge between the two Cretaceous mesas. This ridge consists of Birdrong Sandstone and the major fault plane lies along the eastern side of the ridge. The simplest interpretation is that the Cretaceous rocks have been dragged up by the fault and there was rollover next to the fault. This may be oversimplified, as the steeply dipping Cretaceous rocks appear to abruptly meet flat-bedded Cretaceous rocks; at least one antithetic fault may be present, and blocks may have been rotated rather than simply folded.

Locality 29: Hummocky cross-stratification, Paddys Outcamp

Location: In breakaways just northwest of Paddys Outcamp, Middalya. This stop is useful as an adjunct to the Muderong Shale type area to see some hummocky cross-stratification if other localities are not visited.

Access: As for Muderong Shale type area. At the turn-off to Twin Bores near Paddys Outcamp, turn west and drive cross-country about 300 m up to the southerly facing breakaways.

Time: 20 minutes total.

Geology: Hummocky to swaley cross-stratification, with convex-upward topsets and a set width of about 1 m, is reasonably well exposed in the breakaways of Nalbia Sandstone immediately northeast of Paddys Outcamp. A few shelly coquinas are exposed below the main hummocky, cross-stratified interval. They contain a low-diversity, stunted, death assemblage, which reflects restricted circulation, harsh life-conditions, and storm transport and concentration of the shells.

Locality 30: Birdrong Sandstone type area

Location: 1 km south of Birdrong Spring.

Access: Four-wheel drive essential, dual range advisable. From Mardathuna, drive via Kennedy Tank to Kelly Yard Tank. A track goes from there to Scooped Hole Spring and Birdrong Spring. The sandy creek bed 5 km north of Kelly Yard Tank may be difficult to cross with heavily ladden vehicles. The final approach to the type section from Birdrong Spring requires cautious cross-country driving from near the spring — it is quicker to walk.

Time: Allow a full day from Mardathuna if the station track has not been graded recently, otherwise it may be possible to make a return trip in just over half a day.

Notes: Advise Mardathuna Homestead before entry and check on the access. Severe rain could destroy the track and render the area virtually inaccessible.

Geology: The type section of the Birdrong Sandstone (Fig. 20) is the thickest, continuous section of Birdrong Sandstone in the Kennedy Range area. Most of the section is in a westerly facing breakaway about 400 m west of the Kennedy Fault System. The basal contact, between the Permian Coolkilya Sandstone and the lower fluvial facies, is exposed in the gully below the main face. Exposure of the overlying bioturbated facies is complete, but indistinct. Weathered faces appear massive but are actually bedded; details of bedding and bioturbation can be seen if the face is dug out or scraped off. The Mardie Greensand is not present above the Birdrong Sandstone; instead, the Muderong Shale rests on non-glauconitic bioturbated sandstone. The contact is taken at a prominent ferruginous layer near the top of the breakaway.

The Muderong Shale is very poorly exposed above the type section. Partial sections can be found in gullies to the east on the northerly facing slope. These consist primarily of massive purple claystone, similar to the type section of the Muderong Shale. The Windalia Radiolarite caps the hill and is typical of the unit in outcrop. Silcrete profiles are present locally.

Peedamullah Shelf: Lower Cretaceous

Background geology

The Neocomian–Turonian succession is divisible into two subcomponents, both of which are predominantly siliciclastic. The first contains Berriasian to Valanginian sedimentary rocks (primarily the Barrow Group) and is sandy; the second contains Valanginian–Hauterivian to Turonian sedimentary rocks (the Winning Group) and is commonly fine grained, except for a basal sandy facies. The Winning Group was deposited after tectonic activity associated with rifting in the Mesozoic sub-basins had largely ceased and planation of most of the onshore Carnarvon Basin had occurred. Pelagic marine-shelf sedimentation became dominant in the late Aptian, when deposition of the Windalia Radiolarite began. The Nanutarra Formation and Yarraloola Conglomerate are marginal units for the uppermost Barrow Group and lower Winning Group.

Barrow Group: The Barrow Group was deposited from the Berriasian until the Valanginian, and is a delta-basin complex that built north from the Cape Range area into the Exmouth and Barrow Sub-basins. The provenance was the northern Gascoyne Platform and, to a lesser extent, the Pilbara Block and Hamersley Basin. The Barrow Group sensu stricto is not exposed, but outcrops of Nanutarra Formation and Yarraloola Conglomerate on the Peedamullah Shelf correlate with the uppermost part of the group. Near Barrow Island, it is about 1 km thick, but exposed correlatives are less than 100 m thick. The complex was abandoned when tectonism associated with pull-apart along the western margin disrupted its fluvial feeder system and starved the delta. This was accentuated by falling sea levels.

Winning Group: The Winning Group is a post-breakup, siliciclastic succession, and was deposited mostly in open-marine shelf conditions when terrigenous influx was low. Deposition of the group began during a series of rapid, short transgressions, which formed a major long-term transgressive period. The base of the group is diachronous (Wiseman, 1979); it is progressively younger to the south and spans the interval early Valanginian to Aptian. The remainder of the group is not markedly diachronous and is mid-Aptian to Cenomanian–Turonian in age. Onshore, the group is effectively a widespread veneer over all but the easternmost Carnarvon Basin. The Muderong Shale lenses out south of the Gascoyne River, and the Gearle Siltstone grades laterally into the Alinga Formation in the Shark Bay area.

The group consists of a basal sandy unit (Mardie Greensand, Birdrong Sandstone, part of Nanutarra Formation) overlain by low-energy, siliciclastic shelf deposits; the latter grade to slope deposits in the northernmost parts of the Carnarvon Basin. Radiolarian siltstone intercalations in the Windalia Radiolarite and parts of the Gearle Siltstone have a high silica content, which indicates that dissolved silica in the seawater was abnormally high. In the Carnarvon Basin, the silica could have arisen from contemporaneous submarine volcanism, or from deep tropical weathering of nearby continental areas under conditions of very low terrigenous influx.

Nanutarra Formation: The Nanutarra Formation is a mixed unit that consists primarily of alternating intervals, each 5–20 m thick, of sandstone and siltstone. Broad, fining-upwards cyclicity can be seen in most reasonable outcrops. The most significant outcrops are west of Nanutarra in the Ashburton Embayment, between Jubricoo and Peepingee creeks, and are accessible from the access road to Compressor Station 2 (CS2) on the Dampier – Perth Gas Pipeline (Fig. 21). Here, the Nanutarra Formation developed in two estuary-infill cycles (Units 1 and 2, and 3 and 4) followed by a low-energy transgressive episode (Unit 5). Units 1 to 4 correlate with the Barrow Group, and Unit 5 correlates with, and could be assigned to, the Mardie Greensand. This correlation is based on the similarity of Unit 5 to established Mardie Greensand (in Nanyingee Hill and northern Kennedy Range), the age of the fauna in Unit 5 (Late Neocomian), and the regional extent of the Unit 4 – Unit 5 contact.

The type area for the Nanutarra Formation is north of the Ashburton Embayment, near the access track for microwave tower MLV 22 on the Dampier – Perth Gas Pipeline (Fig. 21). The facies sequence is different from the Ashburton Embayment, and the two areas, while geographically close, can be regarded as separate depositional systems. This is because the present-day topography of Precambrian rocks, which is largely an exhumed Cretaceous landscape (Hocking and van de Graaff, 1978), shows that a Precambrian ridge separated the type area and Ashburton Embayment, and that the two areas were fed by different river systems.

There are five principal lithofacies in the Nanutarra Formation in the Ashburton Embayment. These are:

- cross-bedded sandstone;
- interbedded sandstone and siltstone;
- cross-bedded siltstone;
- horizontally stratified siltstone; and
- bioturbated sandstone.

Cross-bedded sandstone is divisible into planar cross-bedded sandstone and bundle sequences; trough cross-bedding is uncommon. Bioturbation consists primarily of isolated trails on topsets and scattered vertical burrows (*Skolithos* and similar species). Palaeocurrents were mostly westwards. The westward-flowing, cross-bedded intervals are interpreted as fluvial dominated, but in a subaqueous, coastal to estuarine setting (because of the limited bioturbation) where salinity was at least brackish. Well-sorted intervals with westwards palaeocurrents are interpreted as ebb-tidal channel and bar deposits. Intervals that have eastwards palaeocurrents are primarily flood-tidal channel and bar deposits, and tend to form in the upper part of the Nanutarra Formation. Bundle sequences have been recognized only in Pyramid Hill and nearby areas. They are an unequivocal indicator of a shallow, subtidal bar-and-channel setting. In Pyramid Hill, the westward ebb tide was dominant. The main bundle sequence is directly overlain by a cross-set, which was deposited by easterly flowing, flood-tide currents.

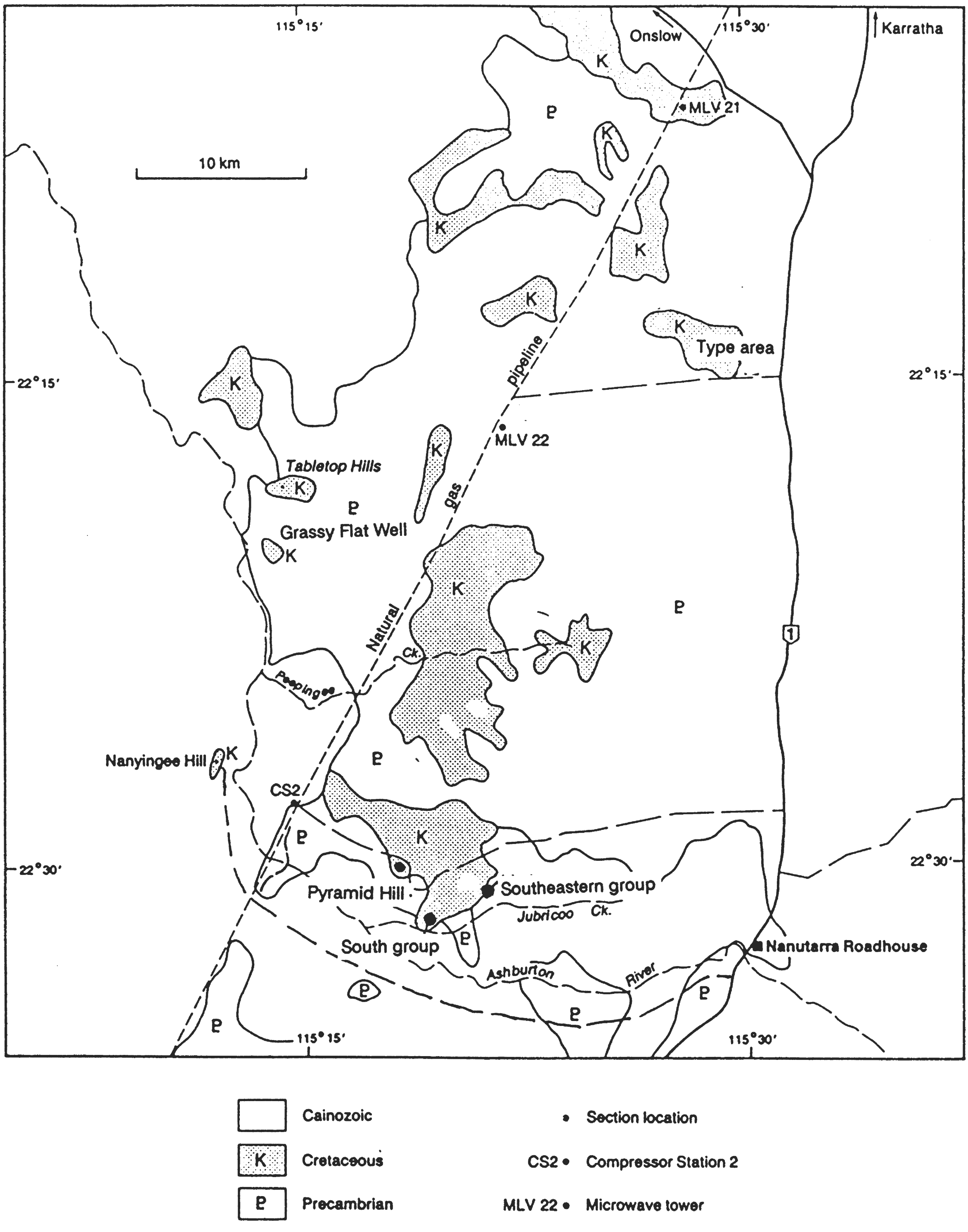


Figure 21. Distribution of Nanutarra Formation and location of sections, Ashburton Embayment to Onslow road

Interbedded sandstone and siltstone ranges from flaser-bedded sandstone through wavy bedding to lenticular bedding. Bioturbation ranges from negligible to intense, and includes both burrows and trails. In the type area, the lower half of the formation grades from glauconitic, interbedded sandstone and siltstone to massive greensand. The facies is commonly present either directly below or above the cross-bedded siltstone facies. In this situation, the depositional environment was either estuarine or intertidal flats adjacent to, and between, channels. Much glauconite was washed in, but some glauconitic intervals probably formed in a protected, subtidal setting. Much of the facies, particularly in Unit 5, is very similar to the dominant facies of the exposed Mardie Greensand.

Cross-bedded siltstone and cross-bedded, interbedded siltstone and sandstone are common in the finer parts of the Nanutarra Formation. Bioturbation is present but not commonly intense. The cross-bedding is commonly large scale (>1 m), low angle, and planar to sigmoidal. The cross-bedding is interpreted to be lateral accretion surfaces on the inside of point bars in coastally situated, fluvial and tidal channels. The cross-beds appear to be very similar to lateral accretion surfaces, which Clifton (1982) described in upper estuarine channels.

There is horizontally bedded or laminated siltstone in Units 2 and 4. Intervals of massive siltstone, in which the massive appearance is commonly due to either bioturbation or weathering, are also included within the facies. This facies developed under conditions of low influx in interdistributary areas and abandoned channels.

Bioturbated sandstone is most common near the top of the Nanutarra Formation. The degree of bioturbation ranges from negligible to intense, so that in some intercalations, bedding is totally destroyed and the rock is best described as homogenized sandstone. Recognizable trace fossils range from vertical burrows to moderately organized feeding trails. In most cases, the original rock can be recognized as part of the interbedded sand and silt facies. The two facies shared similar environmental settings, and there was complete bioturbation during extended hiatuses.

Yarraloola Conglomerate: This is dominated by pebble- to boulder-sized, matrix- or clast-supported conglomerate, although sandstone and siltstone are interbedded. It is exposed in two separate areas: the Robe Embayment and Ashburton Embayment. As with the Nanutarra Formation, the two areas are separated by Precambrian highlands centred around Mount Minnie. In the Robe Embayment, most exposures are mesa cappings and thus, are the remains of a depositional surface that was originally far more extensive and continuous. In the Ashburton Embayment, discontinuous, isolated conglomerate bodies outcrop at the base of the Nanutarra Formation. They are valley-fill deposits, which bear little relationship to exposures of Yarraloola Conglomerate in the Robe Embayment.

In the Robe Embayment, exposures fall into three significant, areally distinct groups. Polymictic conglomerate and sandstone are exposed in the Robe River valley and the upper half of sections in the Red Hill area; this is the dominant lithofacies group. Quartz pebble and cobble conglomerate (the second lithofacies group) dominates the lower half of sections in the Red Hill area; it presumably was sourced by a different river system to the polymictic conglomerate. The third group is in the immediate vicinity of Toongawooroo Hill, and where a very thick (compared to elsewhere) interval of boulder conglomerate is present.

In the polymictic lithofacies group, clasts consist of a variety of rock types from the Hamersley Basin and adjacent areas. Quartzite, chert, and banded iron-formation dominate the assemblage. The conglomerate is interbedded with sandstone, siltstone, and pebbly sandstone. The finer components of the facies group are typical of the Nanutarra Formation, and bioturbation is more abundant in, but not confined to, these intervals. Most conglomerate layers are massive, except for gross divisions more than a metre thick, and sand layers are commonly crudely cross-bedded. The lack of bedding suggests that the group formed primarily by mass-flow processes, and the scattered bioturbation indicates a coastal setting for deposition.

The monomictic facies group forms the lower part of sections between Red Hill and the Onslow road. Polymictic conglomerate commonly overlies it, which suggests two interfingering drainage systems. The group is dominated by vein-quartz clasts, which range in size from granules to small cobbles. In Toongawooroo Hill and the immediate vicinity, the Yarraloola Conglomerate consists of schistose boulders up to 50 cm in diameter, set in a polymictic pebble to cobble conglomerate matrix. This formed by the superposition of locally derived material on the normal, polymictic conglomerate.

The Yarraloola Conglomerate is a high-energy, fluvial-dominated unit, with deposition in a coastal setting. This is indicated by the presence of burrows and rare bivalves in the conglomeratic sedimentary rocks. In broad terms, the unit is a fan-delta deposit. The degree of bioturbation increases towards the top of the unit, as with the Nanutarra Formation, which indicates a relative eustatic rise. The formation is a lateral correlative of the Nanutarra Formation. The same gross regional units, which group into three fining-upwards cycles, can be recognized in both formations.

Locality 31: Nanutarra Formation, southeastern mesa group, Jubricoo Creek

Location: 1.5 km south of access road to CS2, at the southeastern tip of a large area of high mesas.

Access: Four-wheel drive necessary. The turn-off to CS2 is on the west side of the North West Coastal Highway, 6.7 km north of Nanutarra roadhouse, and is marked by a small signpost. For Locality 31, drive 17.7 km west from the turn-off, then turn south around the western end of a large granite-based mesa. Drive cross-country to the southeastern end of a line of mesas, 1.3 km south of the road. A broad, low rise of cobble scree extends to the east. The section is located on the southern side of the point of the ridge.

Time: 2 hours at the section; 30 minutes return trip from the CS2 access road.

Notes: Advise Nanutarra Homestead and contact the pipeline authority as the gates may be locked.

Geology: This section (Fig. 22) is a reference section for the Nanutarra Formation in the Ashburton Embayment. All the units recognized in the Nanutarra Formation can be seen in the section and exposure is good. The broad rise at the base of the section is a weathering lag of Yarraloola Conglomerate, which in this area is assumed to be a valley-fill deposit. Isolated exposures of conglomerate and pebbly sandstone are present in gullies on the rise.

Near the base of the section, there are some anomalously large quartzite boulders in wavily bedded siltstone. Such boulders have been found in several locations, some of which are not close to areas of Precambrian rock, which were topographically high in the Cretaceous. Although they resemble glacial erratics, they were probably emplaced by sheet floods (or even wind) pushing the boulders across a slick, wet, very low friction, silt and mud surface.

Large burrowing bivalves (*Panopea* sp.) are preserved in life position near the top of section in the lower of two intensely ferruginized beds. In one case, the position of the siphon tube can be clearly seen, and indicates that the shell was about 25 cm below the sediment surface when buried. Several specimens are visible about 2 m above a narrow ledge on the easternmost tip of the ridge.

The degree of topographic relief on the Cretaceous basal unconformity can be seen from the top of the mesa by looking to the southwest and north. To the north, a broad, smooth, domed granite ridge extends through several mesas (an alternative route back to the road is over the east end of the dome). To the southwest, there is an extensive area of Precambrian rock capped by a ridge of Nanutarra Formation that has a high depositional dip. More mesas of Nanutarra Formation lie on the far side of the Precambrian area.

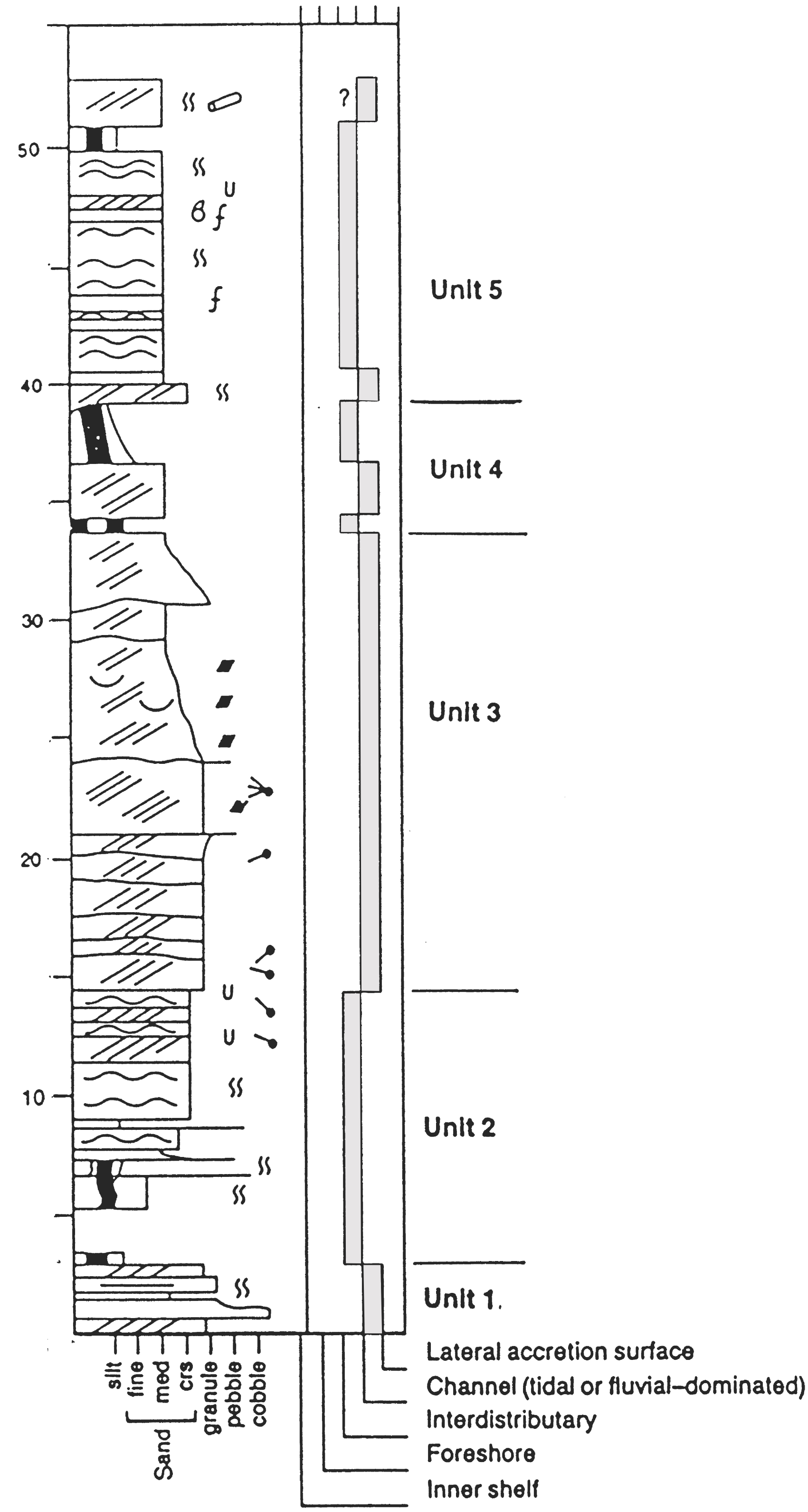


Figure 22. Measured section, Nanutarra Formation, southeastern mesa group near Jubricoo Creek. The section is a remeasured version of Hocking et al. (1987, fig. 93). Thick vertical bars within the section indicate interbedded sandstone and siltstone. See Figure 20 for additional symbols and patterns. Units at the right refer to depositional packages that can be recognized throughout the Ashburton Embayment

Locality 32: Nanutarra Formation, southern mesa group, Jubricoo Creek

Location: 1.6 km south of the access road to CS2, in an isolated group of mesas immediately north of Jubricoo Creek.

Access: Four-wheel drive desirable. The turn-off to CS2 is on the west side of the North West Coastal Highway, 6.7 km north of Nanutarra roadhouse, and is marked by a small sign. Drive through the main group of mesas and a broad, rugged ridge of Precambrian rocks, about 21 km. Turn left onto a track, which branches off to the south around the southwestern margin of the Precambrian. When convenient, turn right and drive cross-country about 200 m to the northeastern end of the mesa group to the south.

Time: 10 minutes drive from CS2 access road; 2 hours for the geology.

Notes: Advise Nanutarra Homestead and contact the pipeline authority as the gates may be locked.

Geology: The basal unconformity between the Nanutarra Formation and subvertically oriented Precambrian rocks is exposed at the southeastern end of the central mesa in this group, and can be traced around the mesa group with moderate ease. Vertical burrows (*Cylindricum*) are present very near the contact and indicate that coastal conditions prevailed from the onset of deposition.

Sections have been measured in the easternmost mesa and at the eastern end of the northernmost mesa (Fig. 23). They are about 200 m apart and show the amount of lateral change in the Nanutarra Formation over short distances. The broad depositional units in the Nanutarra Formation (Units 1 to 4) can be recognized, but the two sections differ in detail, as can be seen on Figure 23. From the top of the second section, large-scale bedding features, including depositional dips, offlap from pre-existing Precambrian rocks, and lateral accretion surfaces can be seen in the northern face of the central mesa in the group.

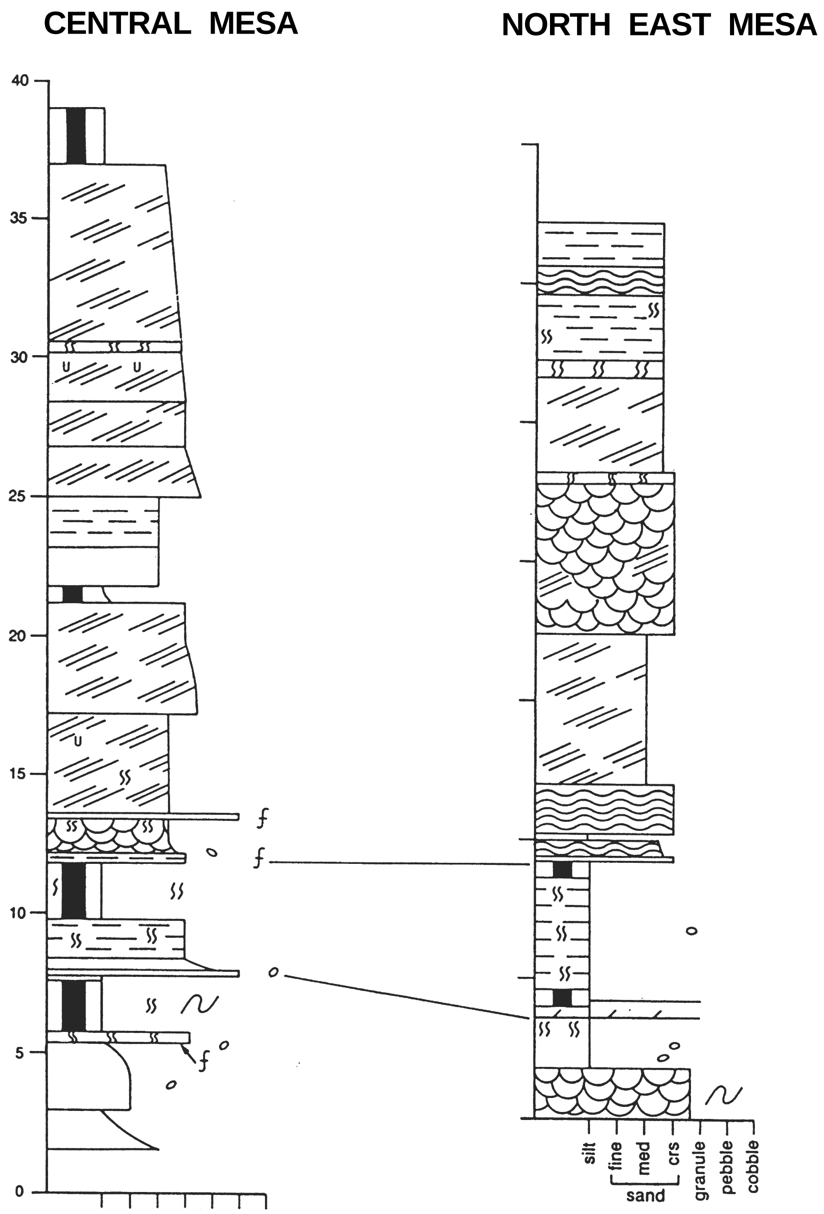


Figure 23. Measured sections, Nanutarra Formation, southern mesa group near Jubricoo Creek. The left-hand section is from the central mesa, and the right-hand section from the northern mesa. Open circles: granules

Locality 33: Nanutarra Formation, Pyramid Hill

Location: 100 m south of the CS2 access road.

Access: Four-wheel drive desirable. The turn-off to CS2 is on the west side of the North West Coastal Highway, 6.7 km north of Nanutarra roadhouse, and is marked by a small sign. Drive through the main group of mesas to a prominent, solitary conical butte (Pyramid Hill) just past a sharp, left-hand bend, 23 km west of the highway. A track leads to a gravel pit beside the hill. The best section is on the south side of the hill.

Time: 1.5 to 2 hours at Pyramid Hill.

Notes: Advise Nanutarra Homestead and contact the pipeline authority as the gates may be locked.

Geology: Units 1 and 2 of the Nanutarra Formation are thin and not well expressed at Pyramid Hill. They lie at the base of the hill below the main exposures. Units 3 and 4 are very well exposed, and show a complete estuary-infill cycle. Unit 5 outcrops above the main exposed face of lateral accretion surface, and is accessible on the northern side of hill (Fig. 24).

Unit 3 (Fig. 24) is a fine- to coarse-grained, cross-bedded sandstone. For most of the unit, currents flowed to the west. Eastward flow occurred near the top of the unit, immediately above two westward-directed bundle sequences. More bundle sequences may be present lower in the unit, but the diagnostic double clay drapes and wrinkly bottomsets cannot be identified unequivocally. The base of the estuary-infill cycle is a gravelly channel-floor lag, several of which are near the base of the main face. These are overlain by a westward-flowing, fluvial-dominated, subtidal channel sequence. Tidal bundles, indicative of waning fluvial influence, are present at the top of this subsequence. They are overlain in turn by an easterly flowing tidal sequence — which abruptly overlies and scours a bundle sequence and indicates channel migration — flat-bedded silty sandstone, and then a cross-bedded, silty, upper estuarine, lateral accretion surface (Unit 4). The top of Unit 4 is a flat-bedded, intensely bioturbated siltstone that was deposited and evolved in an estuarine flat – tidal flat setting.

Unit 5 (Fig. 24) is heavily ferruginized, but originally may have been glauconitic. It fines from cross-bedded sandstone, through bundle sequences, to wavily interbedded sandstone and siltstone. From the bedding and structures, the latter could be either an interdistributary flat deposit or a marine-shelf deposit. The latter option is preferred because of the presence of glauconite in correlative horizons to the west.

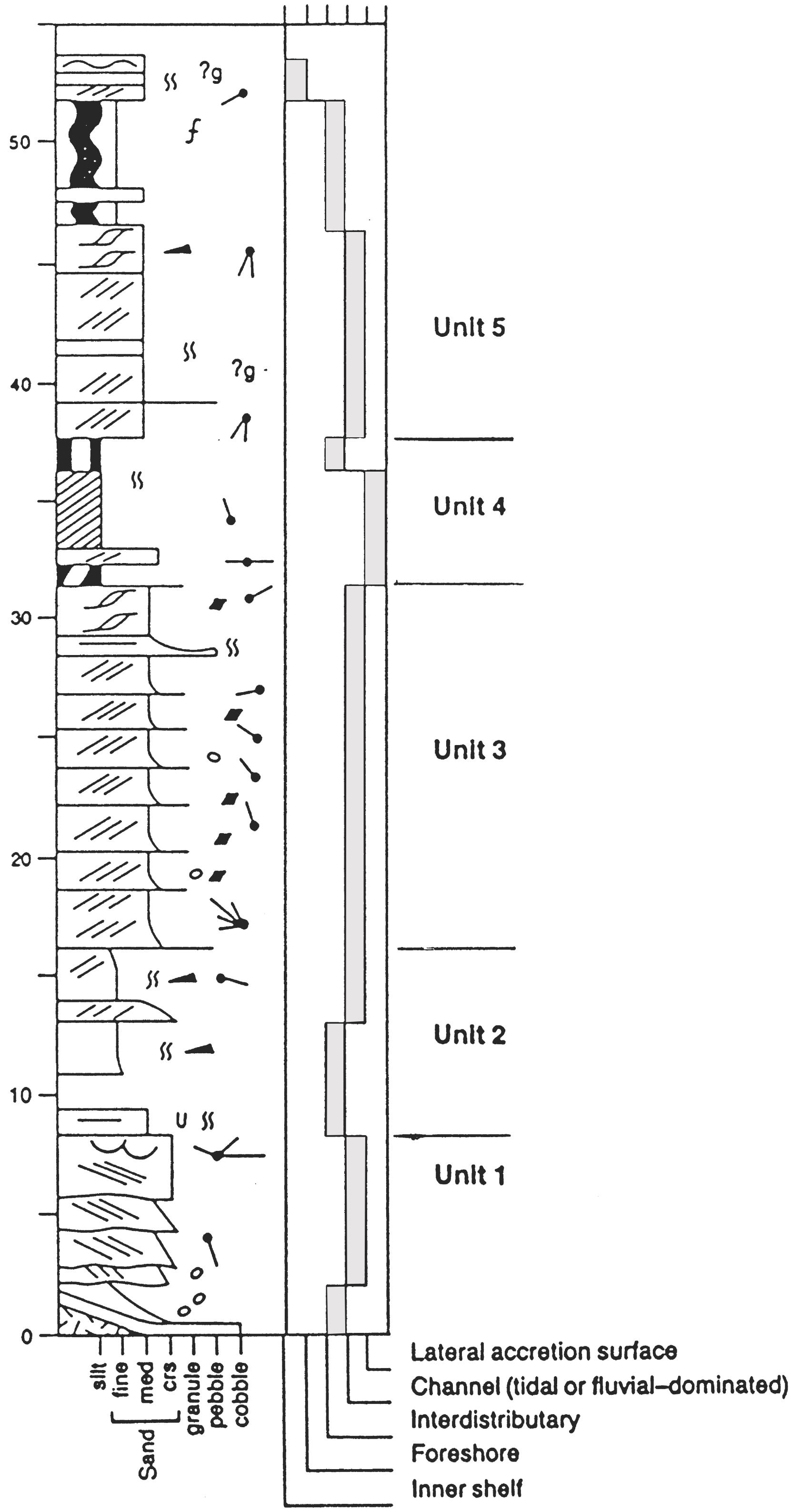


Figure 24. Measured section, Nanutarra Formation, Pyramid Hill. Thick vertical bars within the section indicate interbedded sandstone and siltstone

Locality 34: Mardie Greensand and Windalia Radiolarite, Nanyingee Hill

Location: North end of the northern hill, Nanyingee Hill.

Access: Four-wheel drive desirable. Drive south from Nanutarra roadhouse on the North West Coastal Highway. Turn west at the set of double gates about 1 km south of the bridge (the first set of gates seen). Follow the graded track west to Nanyingee Hill, about 40 km. Alternatively, drive south on the access track for the gas pipeline from CS2, cross the Ashburton River (check the state of the crossing at CS2 or Nanutarra Homestead), and continue south of the river about 1.5 km to the Nanyingee Hill road. Continue past the mining camp between the two hills, and turn off to the northwest end of the two hills.

Time: 50–60 minutes drive from the highway, one way. About 25 minutes from CS2, one way. 30 minutes examination.

Notes: Advise Nanutarra Homestead before entering and ask about locked gates. Advise the pipeline authority in Karratha if you drive along the pipeline an appreciable distance.

Geology: Nanyingee Hill (Fig. 25) consists of Windalia Radiolarite above a greensand, which is now regarded as Mardie Greensand (it was shown as Muderong Shale by van de Graaff et al., 1980). Exposure is adequate but not good; the locality is significant because it is the nearest exposure to the basin margin of unequivocal Mardie Greensand and Windalia Radiolarite. The greensand is exposed in gullies and a couple of ledges around the hill. It is moderately ferruginized, but still recognizably green. The Windalia Radiolarite is moderately to intensely silicified, and a silcrete (greybilly) profile is present at the top of the hill.

The Mardie Greensand is underlain by Nanutarra Formation. The nearest exposure is in the bed of the Ashburton River east of Nanyingee Hill, but the relationship has been established by extensive drilling in the area.

Four kilometres south of the saddle between the north and south hill, a low rise is visible about 1 km west of the track. Access is a 5 minute cross-country drive via claypans. The hill consists of silicified, fine-grained sandstone with scattered wood impressions, and appears to be about the same elevation as the Mardie Greensand further north.

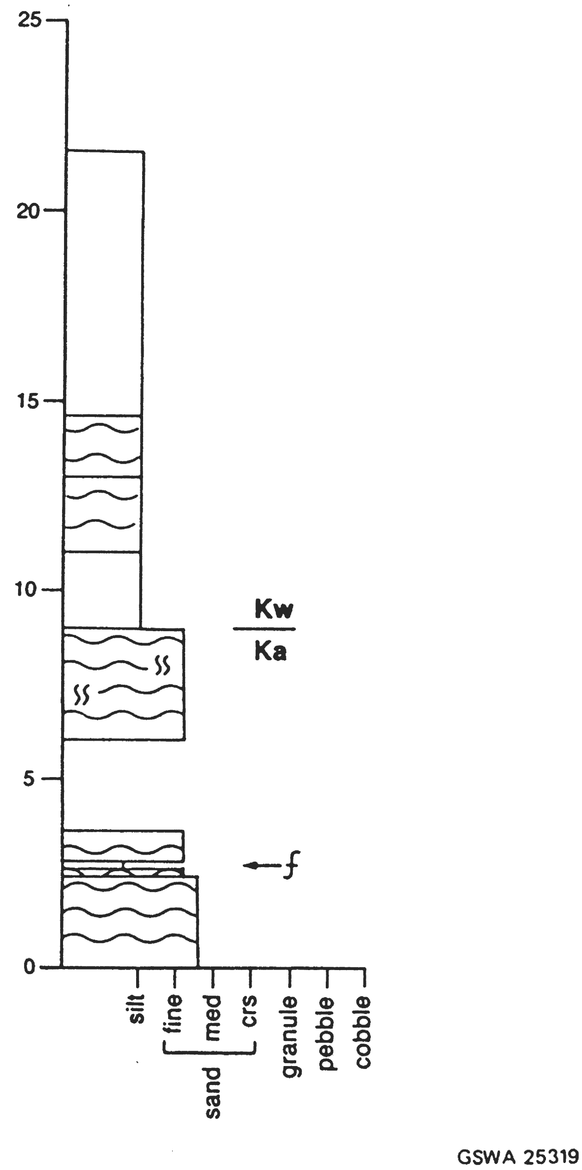


Figure 25. Measured section, Mardie Greensand and Windalia Radiolarite, northwestern end of north hill, Nanyingee Hill. *Kw*: Windalia Radiolarite. *Ka*: Mardie Greensand

Locality 35: Peepingee Greensand Member, Tabletop Hills

Location: Northwest mesa in Tabletop Hills, Minderoo Station.

Time: Approximately 1 hour on the outcrop. One hour drive from Nanyingee Hill, one way.

Access: Drive north from Nanyingee Hill on the track west of the hills to the Minderoo boundary gate (about 1 km). Continue north 5.8 km. There is a faint right-hand branch on a claypan; follow this east-northeast to the river, about 2 km. Check entry and exit of crossing before proceeding, as it is not used frequently. The eastern exit is about 100 m south of the western entry. Continue north to Mount Well, drive 2.7 km north along the west side of the fence, to the northeast bend in the fence. There is a low mesa amidst the granite tors, 200 m to the west. Drive over and examine the section. Continue along the track to Grassy Flat Well. Turn left along the fence and go to the end of the sand dune. A track may curve around the dune and trend northeast, just east of the mesa group; take it if possible. Otherwise, proceed cross-country to the mesa group. These are the Tabletop Hills.

Notes: Advise Minderoo Homestead before entry. Check whether the Ashburton River is flowing, as there is a river crossing near Mount Well.

Geology: The mesa south of Grassy Flat Well (left section, Fig. 26) consists of siltstone overlain by a coarsening-upwards, quartzose sandy interval. The interval is assigned to Units 4 and 5 of the Nanutarra Formation, and it is worthwhile to compare it to the section in the Tabletop Hills. Basement topography is obvious at this site.

At the Tabletop Hills, there is a thick siltstone section exposed between the two northern mesas (Fig. 26, central section). This is overlain by the Peepingee Greensand Member of the Nanutarra Formation, which is probably equivalent to the Mardie Greensand and is correlated with Unit 5 in the Ashburton Embayment. Boulder lags are preserved both at the base of and through the member at the northwestern tip of the northwest mesa (Fig. 26, right section). They are interpreted as the bases of parasequences, and grade laterally into bioturbated greensand over about 30 m. Flasers and clay-filled burrows can be seen near the base of the member on the western side of the northwest mesa. The Peepingee Greensand Member has similar bedding and structures to Unit 5 of the Nanutarra Formation, the Mardie Greensand at Nanyingee Hill, and to the Mardie Greensand in the Kennedy Range area. The similarity in bedding style and presence of glauconite is the basis for correlating these units, as there is little fossil evidence. The member is regarded as an inshore equivalent of the Mardie Greensand.

The large granite ridge to the north is clear evidence that there was significant basement topography in the Cretaceous. To the southeast, further high ridges of granite and metasedimentary rocks (of which Mount Mary and Mount Mistake are named) separate the Tabletop Hills from the remainder of the Nanutarra Formation.

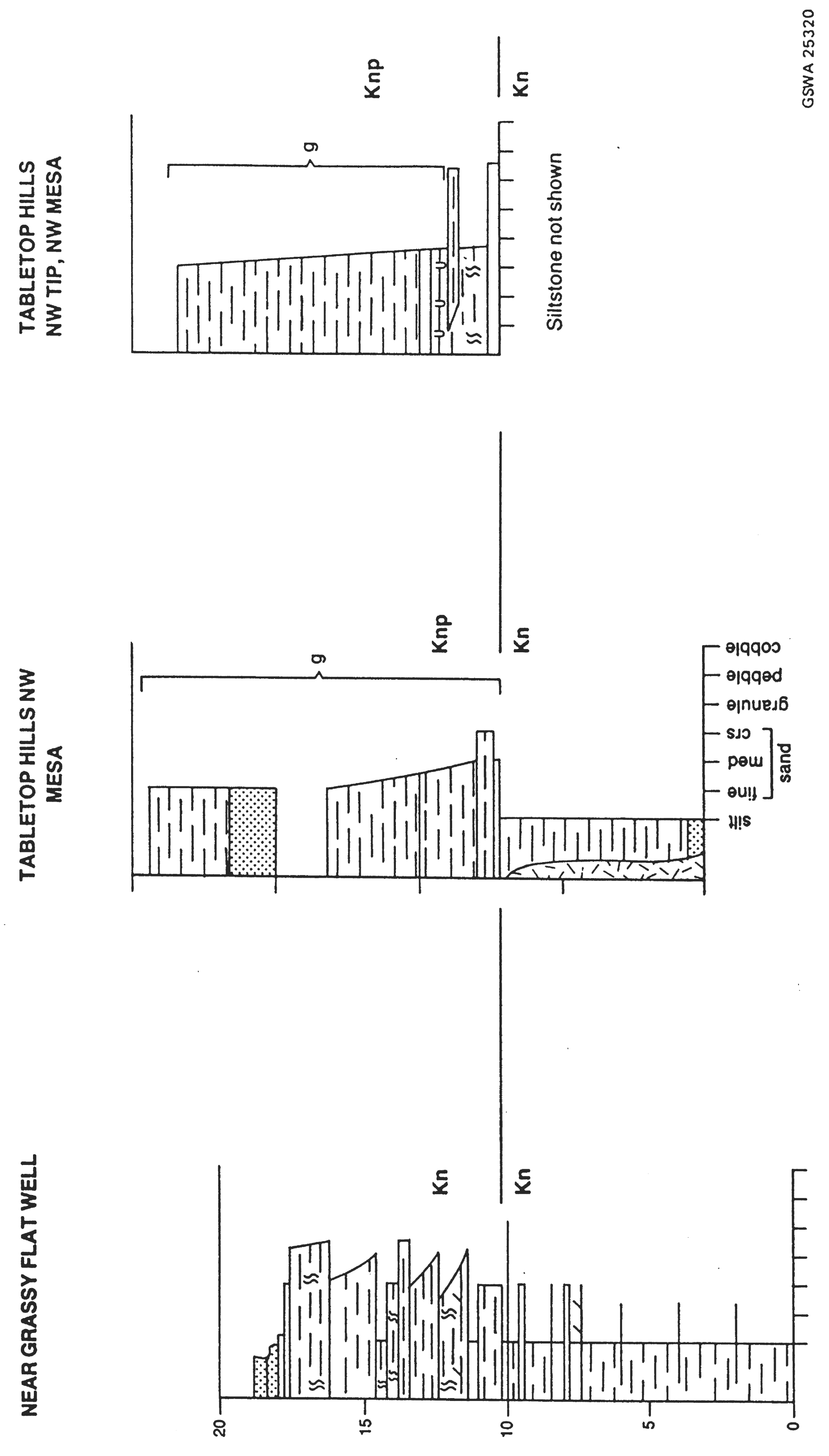


Figure 26. **Measured sections of the Peepingee Greensand Member and underlying Nanutarra Formation, Tabletop Hills, Minderoo Station. *Knp*: Peepingee Greensand Member. *Kn*: Nanuturra Formation. g: glauconite**

Locality 36: Nanutarra Formation, Deep Well area, Uaroo

Location: 3 km south of North West Coastal Highway, approximately 7 km west of the Uaroo turn-off.

Access: Four-wheel drive essential, dual range desirable. There is a large mesa immediately south of the highway, 600 m east of Deep Well and immediately east of a grid over the road. The grid is 40 km southwest of the Ashburton River bridge. Turn south on the west side of the grid, and drive either along the fence or cross-country to a distinctive light-coloured pair of low, pointed peaks about 3 km to the south.

Time: 25–30 minutes drive, return. About 1 hour on the outcrop.

Notes: If convenient, advise Uaroo Homestead before entry.

Geology: The measured section (Fig. 27) is from the gully about 50 m south of the hills, to the top of the western hill. Sandstone and siltstone with abundant plant rootlets are dominant in the lower part of the section. They are overlain by a cross-bedded interval and then a lateral accretion surface in siltstone, which passes through the saddle between the two hills. Thin-bedded and rippled siltstone constitutes most of each hill above the saddle. As with most sections of the Nanutarra Formation, the hills are capped by wavy-bedded, bioturbated sandstone and siltstone.

The section is interpreted as an estuary-infill sequence, much like other sections of the Nanutarra Formation, but located further up a coastal embayment. There are low ridges and hillocks of intensely silicified, channel-fill sandstone in the surrounding area, and ridges of Precambrian metasedimentary rocks a couple of kilometres to each side of the section. The latter are much higher than the Cretaceous rocks.

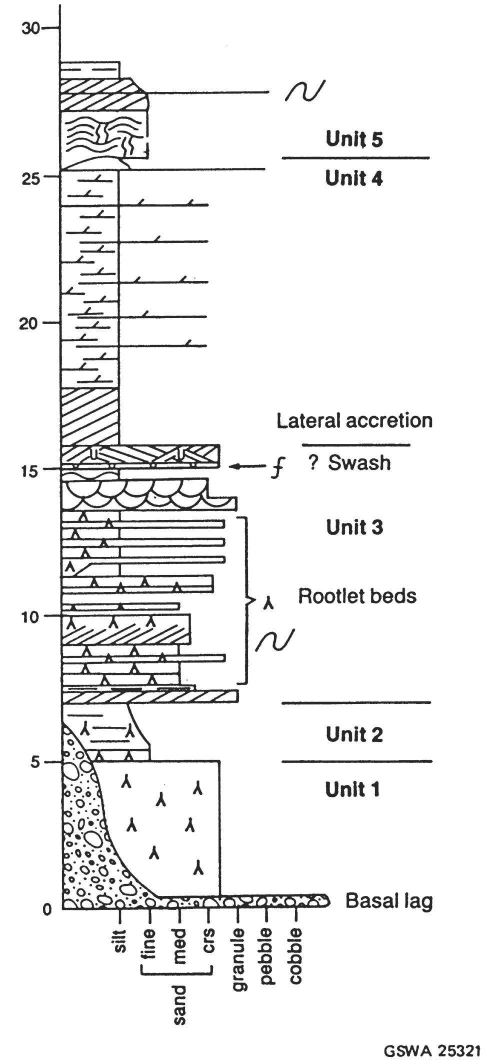


Figure 27. Measured section, Nanutarra Formation, south of Deep Well, Uaroo Station

Locality 37: Yarraloola Conglomerate, near type section

Location: 1 km north of the Robe River, about 6 km east of the North West Coastal Highway.

Access: Four-wheel drive desirable. Turn east onto the old Pannawonica road, directly opposite the turn into Yarraloola Homestead and about 2 km south of the present Pannawonica road. Drive about 6 km, until you can see two mesas about 60 m apart and 1 km south of the road. Drive over to them, cross-country.

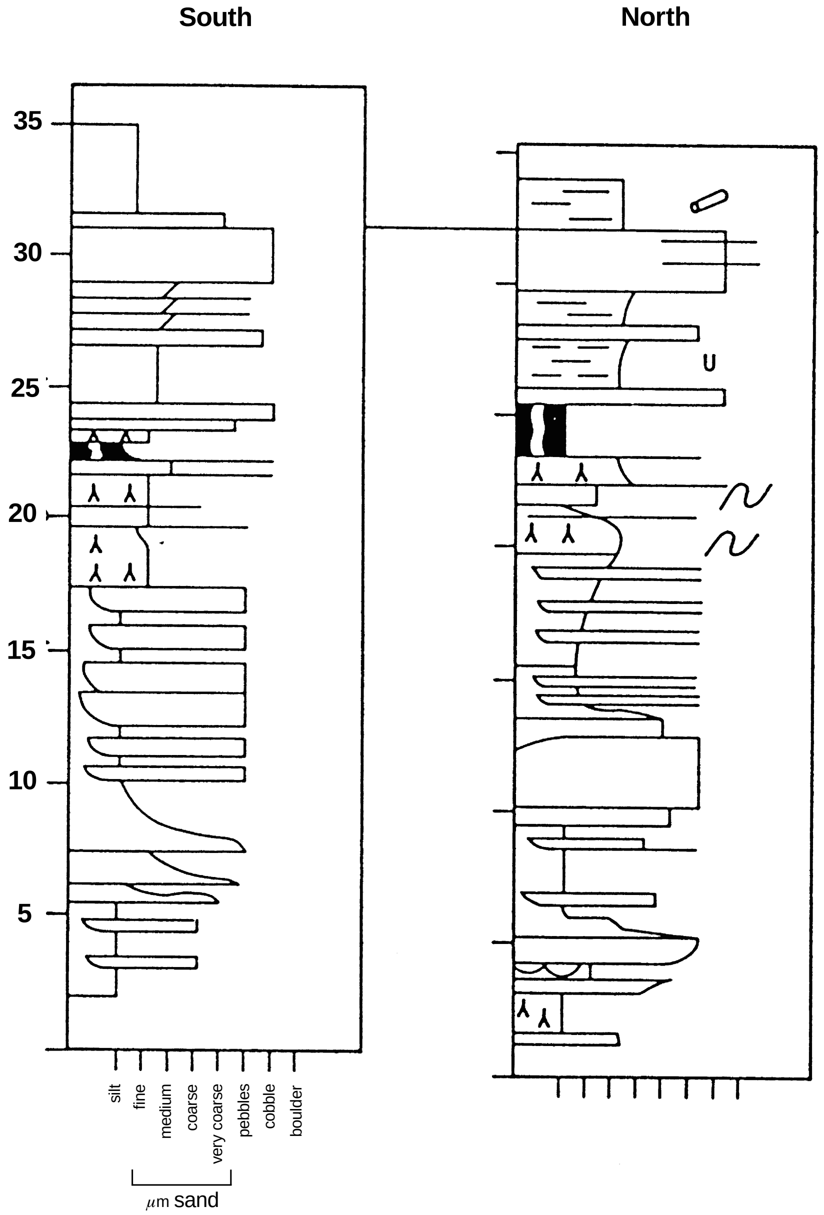
Time: 10–15 minutes drive from the highway, one way. About 60–90 minutes to examine the two sections.

Notes: Advise Yarraloola Homestead before entry as the old Pannawonica road is no longer a public road.

Geology: The sections of Yarraloola Conglomerate in the two mesas (Fig. 28) are much thicker than most sections in the Robe Embayment, because they extend further down hill. Thus, the base of the section is assumed to be older. Lateral change can be assessed by comparing the two sections.

The two sections share the same sequence of broad facies, but there are differences in detail. For example, conglomerate horizons are thicker in the southern hill in the central part of the section, and the horizons with rootlets are thicker in the southern hill, but contorted bedding was only noted in the north hill.

Rootlet horizons are present at the base of the northern hill and in contorted horizons about 20 m up the section. They are also present about 20 m up the southern hill. Wavily interbedded sandstone and siltstone overlie the rootlets in both hills, and burrows are present shortly above that.



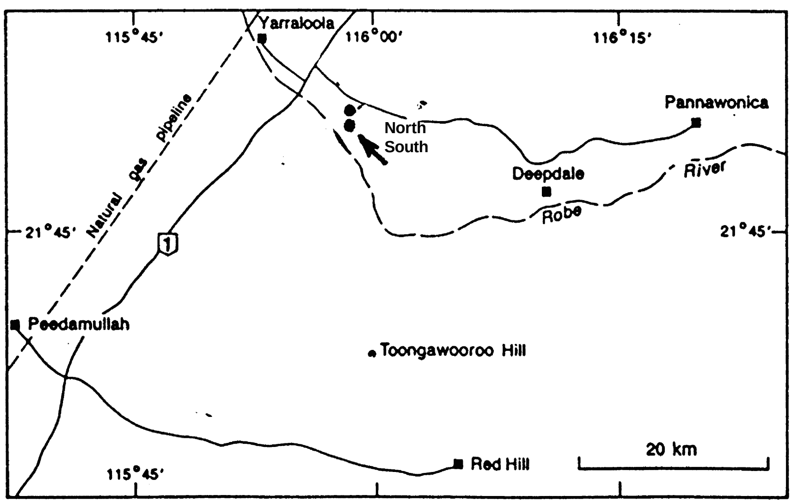


Figure 28. Measured sections, Yarraloola Conglomerate near type section, Robe Embayment

Cape Range area: Miocene to Quaternary

Background geology

Four major cycles of deposition can be distinguished in the Cainozoic, and all are carbonate dominated. The first two, mid-Paleocene to Middle Eocene and Middle–Late Eocene, are exposed in the Giralia Anticline, southeast of Cape Range. The third cycle, Oligocene to Middle Miocene, is exposed in Cape Range and Rough Range, and parts of it (Trealla Limestone, Lamont Sandstone, and Pindilya Formation) extend over much of the onshore Carnarvon Basin.

Late Oligocene and Miocene: There was a substantial break in deposition during the Early–Middle Oligocene, when there was a major phase of duricrust formation in the onshore Northern Carnarvon Basin. Deposition resumed in the Late Oligocene, continued until the late Middle Miocene, and was carbonate dominated. The resultant succession is largely assigned to the Cape Range Group. In the Northern Carnarvon Basin, there was siliciclastic deposition (of quartz arenite and calcareous quartz sandstone) only in the Middle Miocene, on the western flank of Cape Range (Pilgramunna Formation and Vlaming Sandstone) and offshore to the northeast along parts of the Rankin Platform (Bare Formation). Further south, the Lamont Sandstone and Pindilya Formation extended as a siliciclastic veneer as far south as the Murchison River. Offshore, the Cape Range Group is locally more than 1 km thick.

In general, the succession fines northwards from Cape Range, which reflects the overall basin morphology, and coarsens upwards because of basinal shallowing in the Miocene. As with other Cretaceous and Cainozoic successions, the interval is a northward-thickening sheet of sedimentary rocks over the continental shelf and a thin sheet of sedimentary rocks over most of the onshore part of the basin. Progradation of sediment over the continental slope served to extend the continental shelf northwards. The source of sand for the Pilgramunna Formation may have been either the ancestral Gascoyne River (from whence the sand was carried north by longshore drift) or the Lyndon and Minilya rivers.

The carbonates were deposited in environments that deepened from shallow-marine, inner shelf around Cape Range, to deep-marine, outer shelf and slope north of the Rankin Platform (Fig. 3), with the environment deepening northwards from Cape Range. Minor lagoonal deposits are present in the Lake MacLeod area (Denman and van de Graaff, 1982). In the northern areas, the siliciclastic sediments were deposited in shoreface to foreshore environments as shoaling bars and spits (Pilgramunna and Bare Formations, and Lamont Sandstone), which were locally capped by eolian dunes (Vlaming Sandstone). The Pindilya Formation to the south, is a sheet-flood, fluvial and residual unit.

Late Miocene to Holocene: Except in the northern, offshore part of the basin, the Carnarvon Basin was emergent after the Middle Miocene. Duricrust calcrete formed in the Pliocene and Pleistocene during arid periods. The only significant deposition in onshore areas north of Carnarvon was during the late Pliocene and Pleistocene, when thick eolian sands accumulated against the sides of some coastal anticlines. Strandline deposits also flanked the anticlines and infilled intervening synclines. Extensive dune fields of quartz sand (now red) developed in the Late Pleistocene, west of Kennedy Range and east of Exmouth Gulf.

Locality 38: Shothole Canyon

Location: 16 km south of Exmouth from the main road (see Fig. 1).

Access: Two-wheel drive. Take the posted turn to the west 16 km south of Exmouth and follow the road, which ends at the Cape Range 1 wellhead.

Time: 1 hour to 90 minutes return trip.

Notes: Parts of Shothole Canyon are within Cape Range National Park, so sample collection should be arranged with the ranger or CALM in Perth.

Geology: The drive into Shothole Canyon provides easy access to the major units in the Cape Range Group, the Trealla, Tulki, and Mandu Limestones, as one drives from the east limb to the core of the anticline. The Trealla Limestone forms the first low ridges at the foot of the range and is a whitish, shelly, relatively pure limestone. Algal boundstone caps the unit and can be seen south of the track after the first major creek crossing within the range, about 3.4 km west from the turn-off. The Tulki Limestone is a characteristically pink, nodular limestone and is exposed in the canyon proper. Shoaling was present locally, as low-angle cross-bedding can be seen in one large face north of the road. Nodular Tulki Limestone is readily accessible on the south side of the road about 5.5 km from the turn-off.

The Mandu Limestone is a white to yellow, soft marly limestone that is exposed in the core of the anticline. Large lepidocyclinid foraminifers are excellently exposed in a northerly facing undercut immediately south of a carpark on the south side of the road, shortly before the road turns into a major left-hand (southwest) branch of the canyon. A cyclic section of Mandu Limestone is well exposed in an undercut cliff on the north side of the road, 9.3 km west of the turn-off. There, a greyish, burrowed hardground (top of cycle) is present about 2 m above creek level, and is overlain by a foraminiferal and shelly coquina (base of next cycle). This grades up into a massive, sparsely foraminiferal, cream-coloured, marly limestone.

Locality 39: Charles Knife Road

Location: 23 km south of Exmouth, on the main road.

Access: Two-wheel drive.

Time: 1 hour return from the main road.

Notes: The road is named after Charles Knife, an oil company accountant. In search of a route for vehicles to the top of Cape Range (so that a petroleum exploration well could be located on top of the range), he explored the east side of the range, largely on foot, and worked out the route to the top, which is now Charles Knife Road. One narrow part of the road, where cliffs drop away on either side, traverses an arch.

Geology: The drive up Charles Knife Road to the top of the range offers excellent views of the canyons. The views show the shape of the anticline, gross colour variations in the limestone units, and overall morphology of the range and fringing coastal plain. The wellhead for Cape Range 2, a minor gas discovery in the Jurassic Dingo Claystone, is near the end of the road.

Locality 40: Mowbowra Creek mouth

Location: 7 km south of Exmouth.

Access: Two-wheel drive. Turn east off the main road, 7 km south of Exmouth, onto a track just north of the Mowbowra Creek crossing. Follow the track along the north bank of Mowbowra Creek to the creek mouth.

Time: 45 minutes return from the main road.

Geology: A Pleistocene fossil coral reef is exposed near sea level at the mouth of the creek. This is overlain by the Mowbowra Conglomerate Member of the Bundera Calcarenite. This is a limestone cobble and boulder conglomerate similar to, but older than, those that infill the present-day creek beds. The clasts are Miocene limestone from the Cape Range. Conglomerate also forms within and beneath the reef (Hocking et al., 1987, fig. 120). The conglomerate forms a low ridge that can be traced as far north as the Exmouth Caravan Park.

Locality 41: Wave-cut terraces, southwest of Vlaming Head

Location: 4 km southwest from Vlaming Head lighthouse.

Access: Drive to Vlaming Head from Exmouth. Continue along the road down the west side of the range to the national park and Yardie Creek. About 5.2 km south of the turn to Vlaming Head lighthouse, turn east onto a track that leads over a broad ridge to the range. Follow the track as far as practical towards the range (about 1.5 km). Four-wheel drive may be necessary for the last parts of the track.

Time: Approximately 1 hour return.

Geology: The track lies along line A of van de Graaff et al. (1976). The main road and initial part of the track are on the youngest recognized wave-cut terrace, the Tantabiddi Terrace (Fig. 29). This terrace is about 125 000 years old, based on radiometric dating of corals (Veeh et al., 1979). The broad rise is a Tantabiddi dune ridge. About 1 km east of the road, the track crosses the second oldest terrace, the Milyering Terrace. The intermediate terrace, the Jurabi Terrace, is obscured by the Tantabiddi Member. In and around the track, about 200 m east of a large fig tree and sinkhole, the terrace shows a spur and groove morphology in which grooves cut into the Tulki Limestone are infilled by Pleistocene conglomerate and coralgal limestone of the Milyering Member (Hocking et al., 1987, fig. 118). The terrace has been exhumed extensively around the track, and large expanses of terrace with a veneer of conglomerate and sandstone can be seen if the spinifex cover is not dense.

The track then climbs onto deposits associated with the oldest terrace, the Muiron Terrace, and finishes near an abutment unconformity between the Pleistocene and Miocene (van de Graaff et al., 1976, fig. 32C). From the end of the track, clamber south around the point of the ridge (about 100 m), and the abutment unconformity is exposed on a southerly facing, vertical face near a small, westerly facing cave. The unconformity dips west at 70° and is between reddish, eolian Exmouth Sandstone (Muiron Member) and whitish, cross-bedded sandy limestone of the Pilgramunna Formation. If desired, continue up the range to the contact between the Pilgramunna Formation and Vlaming Sandstone.

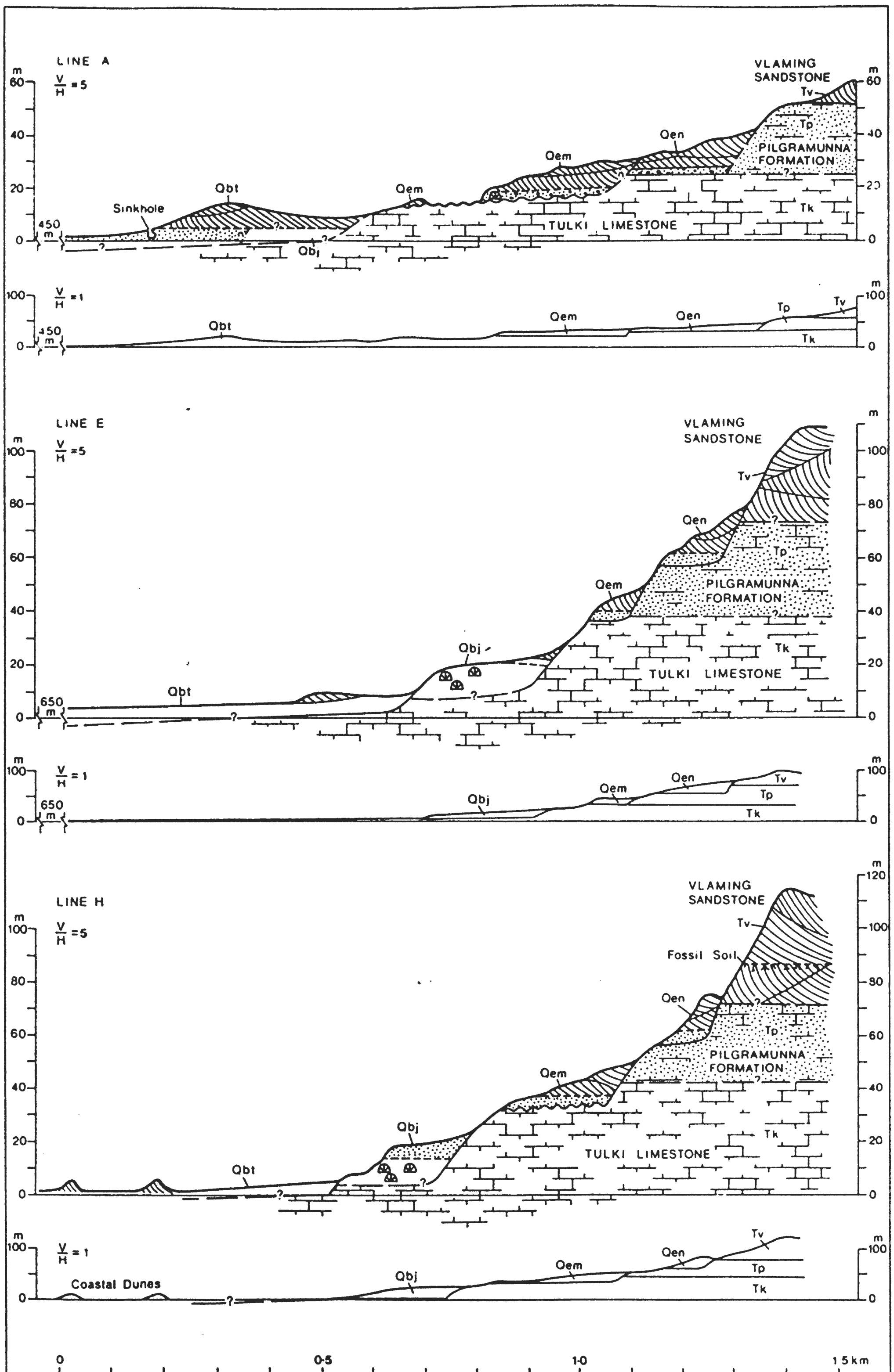


Figure 29. Traverses through emerged wave-cut terraces and terrace deposits, west side of Cape Range (from van de Graaff et al., 1976, fig. 33). Line A is south of Vlaming Head, line E is north of Mandu Mandu Creek, line H is 20 km south of Yardie Creek. *Qbt*: Tantabiddi Member, *Qbj*: Jurabi Member, *Qem*: Milyering Member, *Qen*: Muiron member, *Tk*: Tulki Limestone, *Tp*: Pilgramunna Formation, *Tv*: Vlaming Sandstone

Shark Bay area: Quaternary

In the Shark Bay area, on the western coastline of Western Australia, the peninsulas of calcareous and quartzose coastal dunes delineate a set of shallow-marine basins, which have variable restricted marine circulation. Hamelin Pool and Lharidon Bight are hypersaline basins less than 10 m deep, which have extensive fringing tidal flats and beach ridges (Hocking et al., 1987). Hamelin Pool is barred on the north by the Faure Sill, a seagrass and limesand bank that extends from the northern tip of the Nanga Peninsula east to Yaringa Point. Lharidon Bight is barred less completely by a similar sill that extends west to the Peron Peninsula near Monkey Mia. Algal mats dominate the tidal flats and shallow subtidal areas, and stromatolites extend around Hamelin Pool in the tidal and shallow subtidal zones south of the Faure Sill. The distribution and morphology of the stromatolites are controlled by prevailing wind direction, wave translation direction, the presence of a hard substrate, and the absence of grazing predators (Playford and Cockbain, 1976; Playford, 1980). Wide beach ridges and prograding spits are present behind and on the tidal flats. They are composed of small specimens of the bivalve *Fragum erugatum*, the growth of which has been stunted by the hypersaline conditions.

Locality 42: Stromatolites and beach ridges, Hamelin

Access: Turn off the North West Coastal Highway onto the Denham road at the Overlander, and drive to the marked turn-off, about 1 km past the turn-off to Hamelin Station. Follow the road past the Boolagoorda camping area and shops (on your right) to the parking area. The stromatolites are best exposed at low tide. Boardwalks and information plaques are present.

Geology: Old wagon tracks can be seen cutting through the algal mats and stromatolites south of the boardwalk, where wool wagons were loaded prior to export by road from Hamelin. These show the very slow growth rate of the mats and stromatolites, and emphasize the point that you should disturb living algal mats and stromatolites as little as possible. More recent bike and vehicle tracks also cross and destroy the mats.

About 200 m north of the fence, there are old shell-brick pits in the beach ridges. Access to these is via a walking track over the ridge from Boolagoorda. Blocks from these and similar pits were used to construct many of the buildings in the Shark Bay area (e.g. Hamelin Homestead). Usage is now restricted to maintenance of existing buildings around Shark Bay. The pits are in consolidated ridges of *Fragum erugatum*.

Locality 43: Quaternary geology, Yaringa

Access: Just south of Yaringa Homestead, the highway passes between a few mesas and breakaways. A graded track leads to a signposted tourist lookout on the top of one mesa.

Geology: The mesas and breakaways are composed predominantly of Upper Cretaceous Toolonga Calcilutite. Cappings of Eocene Giralia Calcarenite and Miocene Trealla Limestone are present locally.

The Quaternary morphology of the Gladstone Embayment can be seen from the lookout (Fig. 30). The breakaways outline the Pleistocene coastline, which consisted of low sea-cliffs and re-entrants. Many of the playas are floored in Toolonga Calcilutite, and a syncline axis is present just north of the lookout. Pleistocene marine and beach sedimentary rocks (Bibra and Dampier Limestones) overlie the Cretaceous and are exposed around the margins of the playas.

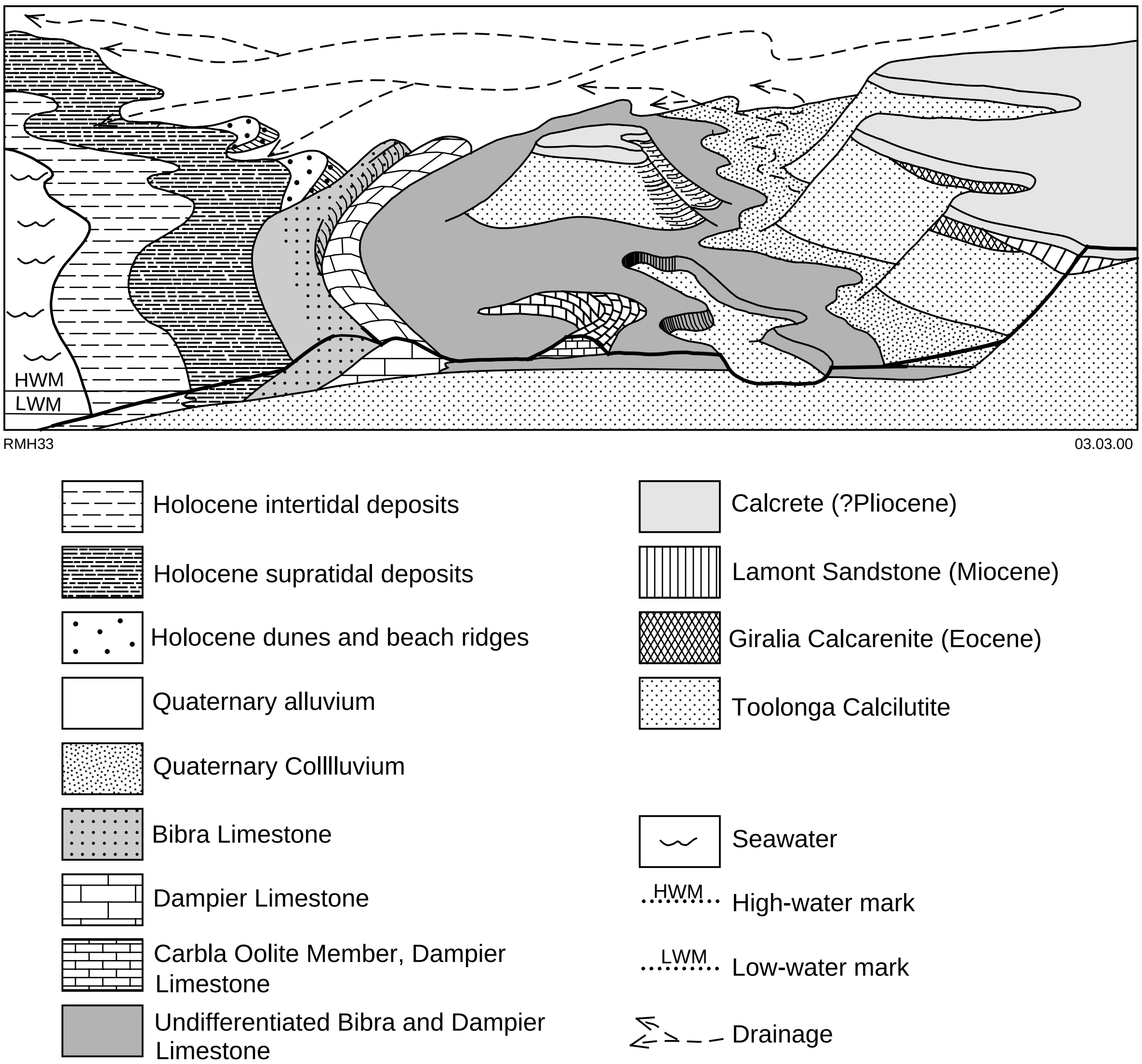


Figure 30. Quaternary morphology of the Gladstone Embayment (from Denman et al., 1985)

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