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GEOLOGY OF THE KALBARRI AND MINGENEW AREAS — A FIELD GUIDE

by AJ Mory and RM Hocking



Geological Survey of Western Australia



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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**by
AJ Mory and RM Hocking**

Perth 2008

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Geology of the Kalbarri and Mingenew areas — a field guide

by

AJ Mory and RM Hocking

This guide covers the regional geology of the western margin of Western Australia and the Kalbarri and Mingenew areas. Descriptions of regional geology and of the Kalbarri area in this guide are derived primarily from the following field guides: Record 2000/10 (Hocking, 2000), Record 2005/9 (Mory et al., 2005), and Record 2006/19 (Hocking and Mory, 2006).

Regional geology

The greater Carnarvon Basin (Hocking et al., 1987; Hocking, 1990; Mory et al., 2003) extends onshore from Geraldton to Karratha along the western and northwestern coastline of Western Australia (Fig. 1), west and northwest of Archean and Proterozoic cratons and orogens. The basin covers about 115 000 km² onshore and 535 000 km² offshore to the continental–oceanic crust boundary. The basin is divisible into the Southern Carnarvon Basin, containing primarily Paleozoic sedimentary rocks with a Mesozoic and Cenozoic veneer, and the Northern Carnarvon Basin, which was the primary Mesozoic depocentre (Hocking, 1994; Tyler and Hocking, 2001). At about 27°S, the basin is transitional southwards into the Perth Basin, which in turn extends southwards to the southwest tip of Western Australia, west of the Archean Yilgarn Craton.

Sedimentary rocks in the greater Carnarvon Basin range in age from Ordovician to Holocene, and can be divided into twelve distinct packages of sedimentary rocks (Fig. 2), only some of which outcrop. These packages reflect major depositional episodes, are primarily unconformity-bounded, and each has unifying lithological characteristics. The packages are based on the successions seen in Phanerozoic basins throughout Western Australia (Trendall and Cockbain, 1990), rather than only in the Carnarvon Basin.

The three Paleozoic packages (Ordovician to mid-Devonian, Late Devonian and Early Carboniferous, and Late Carboniferous and 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 and earliest Cretaceous, and Early and 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 (Longley et al., 2002). They are pre-rift trough-infill (Triassic); rift valley (Jurassic); and post-breakup, trough-infill, and restricted circulation, trailing-margin successions (Cretaceous) respectively.

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

A notable feature centred directly east of Hamelin Pool is the Woodleigh impact structure, a 120 km-diameter, multi-ring circular impact structure close to the Devonian–Carboniferous boundary in age (Uysal et al., 2001, 2005) that is buried below 60–200 m of Cretaceous marine strata and, near the impact epicentre, Lower Jurassic lacustrine deposits. There is virtually no surface expression of the structure apart from some drainage that implies Cenozoic movements along the outer ring faults, probably reactivated during Miocene compression (Iasky and Mory, 1999; Mory et al., 2000).

The Perth Basin (Playford et al., 1976; Cockbain, 1990; Mory and Iasky, 1996) is a north–south elongate rift or trough that covers about 100 000 km² along the western coast of Australia, and is underlain by the Pinjarra Orogen. This outcrops as fault-bounded, mid-basin ridges in the Leeuwin and Northampton Complexes. The northern Perth Basin contains mainly clastic rocks of mid-Carboniferous to Early Cretaceous age (Fig. 3), deposited in a rift system that culminated with the breakup of Gondwana in the Early Cretaceous. Two major tectonic phases are recognized: Permian extension in a southwesterly direction and Early Cretaceous transtension to the northwest during breakup. Sinistral and dextral movements, respectively, are inferred along the major north-striking faults during these phases, especially at breakup, which caused horizontal displacements, wrench-induced anticlines, and further faults (Harris, 1994; Mory and Iasky, 1996; Song and Cawood, 2000). Transgressive marine deposits

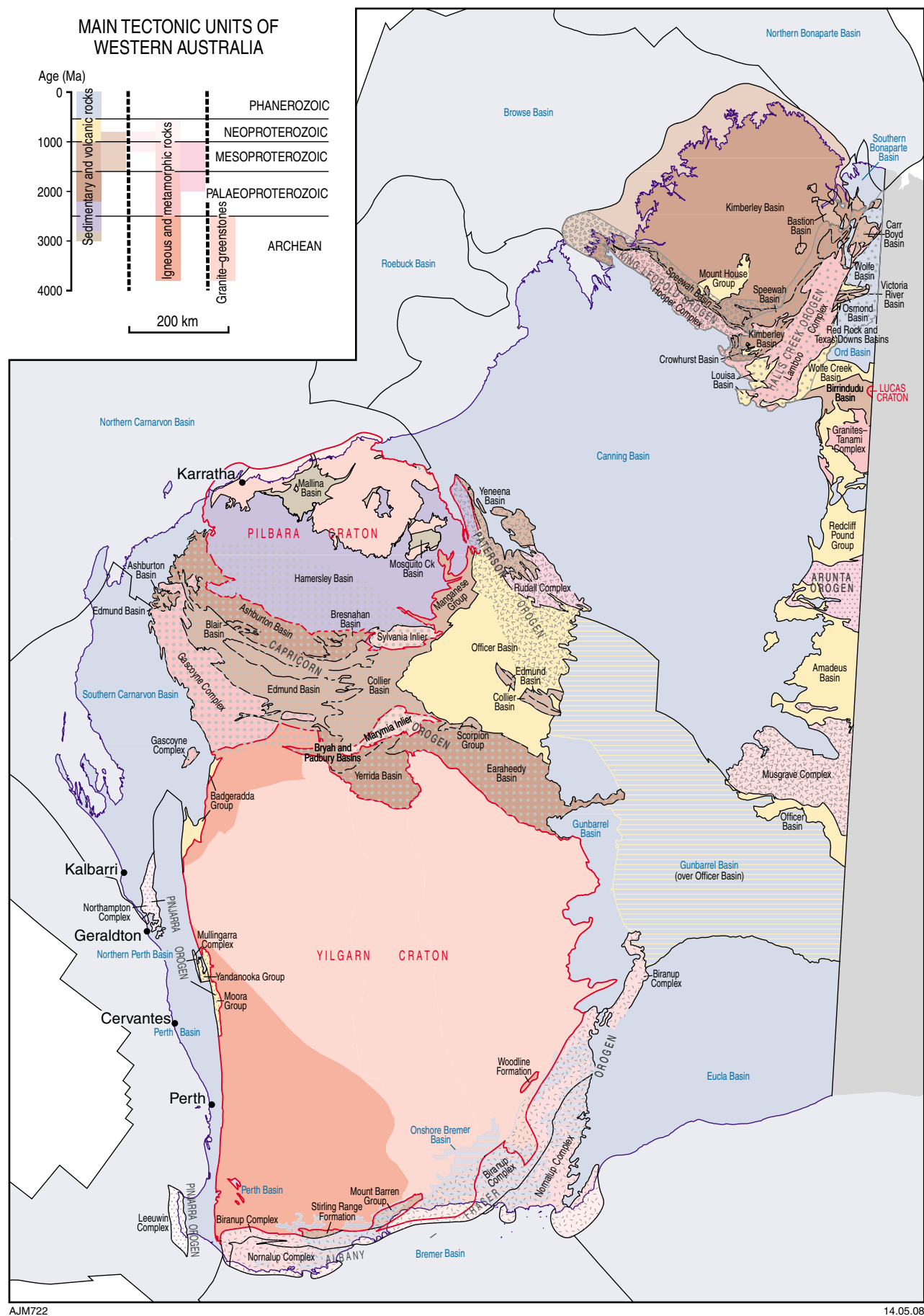


Figure 1. Tectonic units of Western Australia, after Tyler and Hocking (2001)

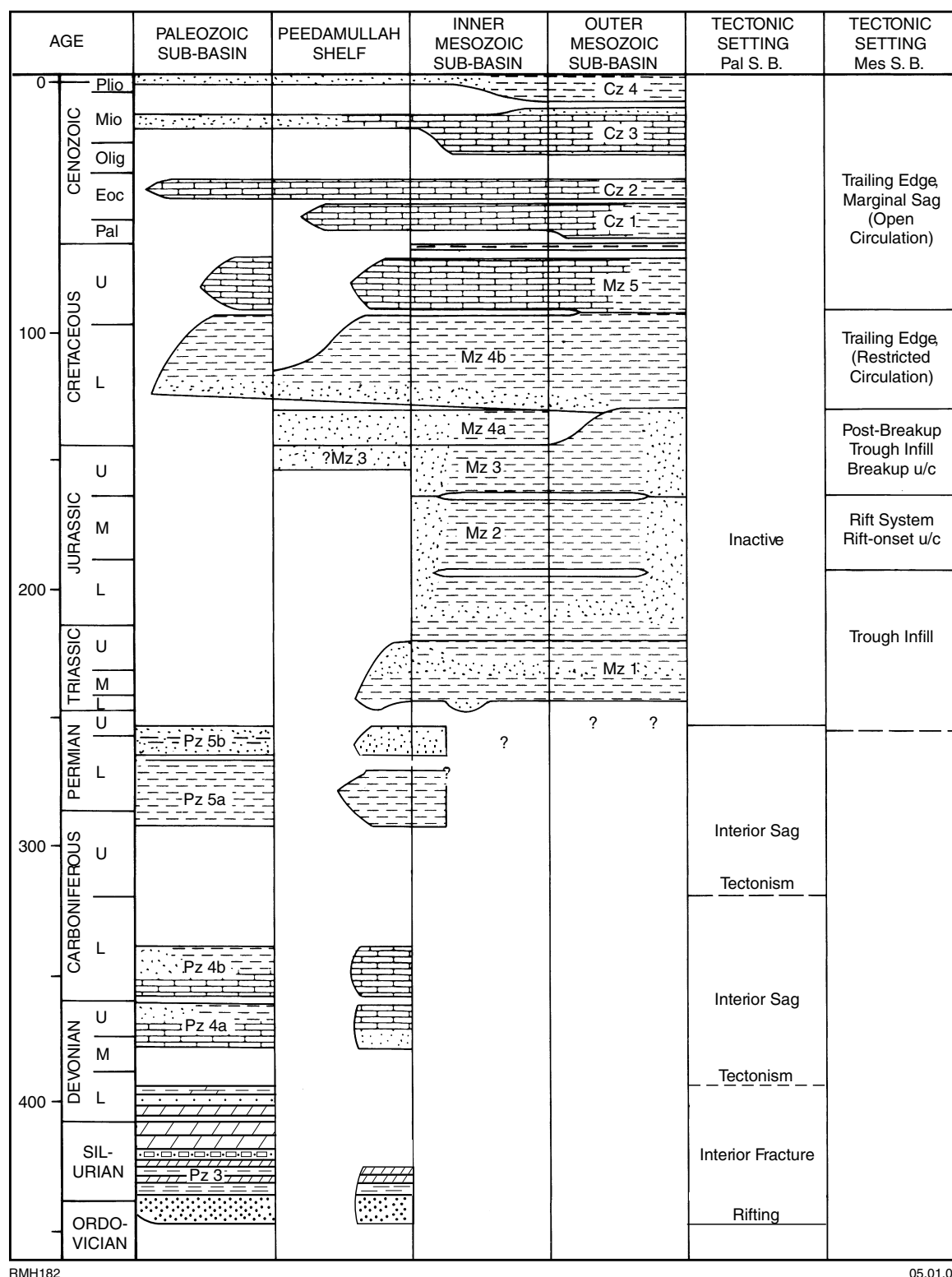


Figure 2. Depositional packages and tectonic development of the greater Carnarvon Basin, after Hocking (2000). Alphanumeric codes refer to major depositional packages, and are placed where the packages are most significant

characterize the late Early Cretaceous and Cenozoic post-breakup phase of deposition. In the onshore Perth Basin these are virtually undeformed and, as in the central and western Southern Carnarvon Basin, Cenozoic sand and ferruginous duricrust cover most of the basin.

Figure 4 shows the excursion localities for the Australian Earth Sciences Convention 2008 field trip to the Kalbarri and Mingenew areas, as well as the regional geology and tectonic units, superimposed over a digital elevation image.

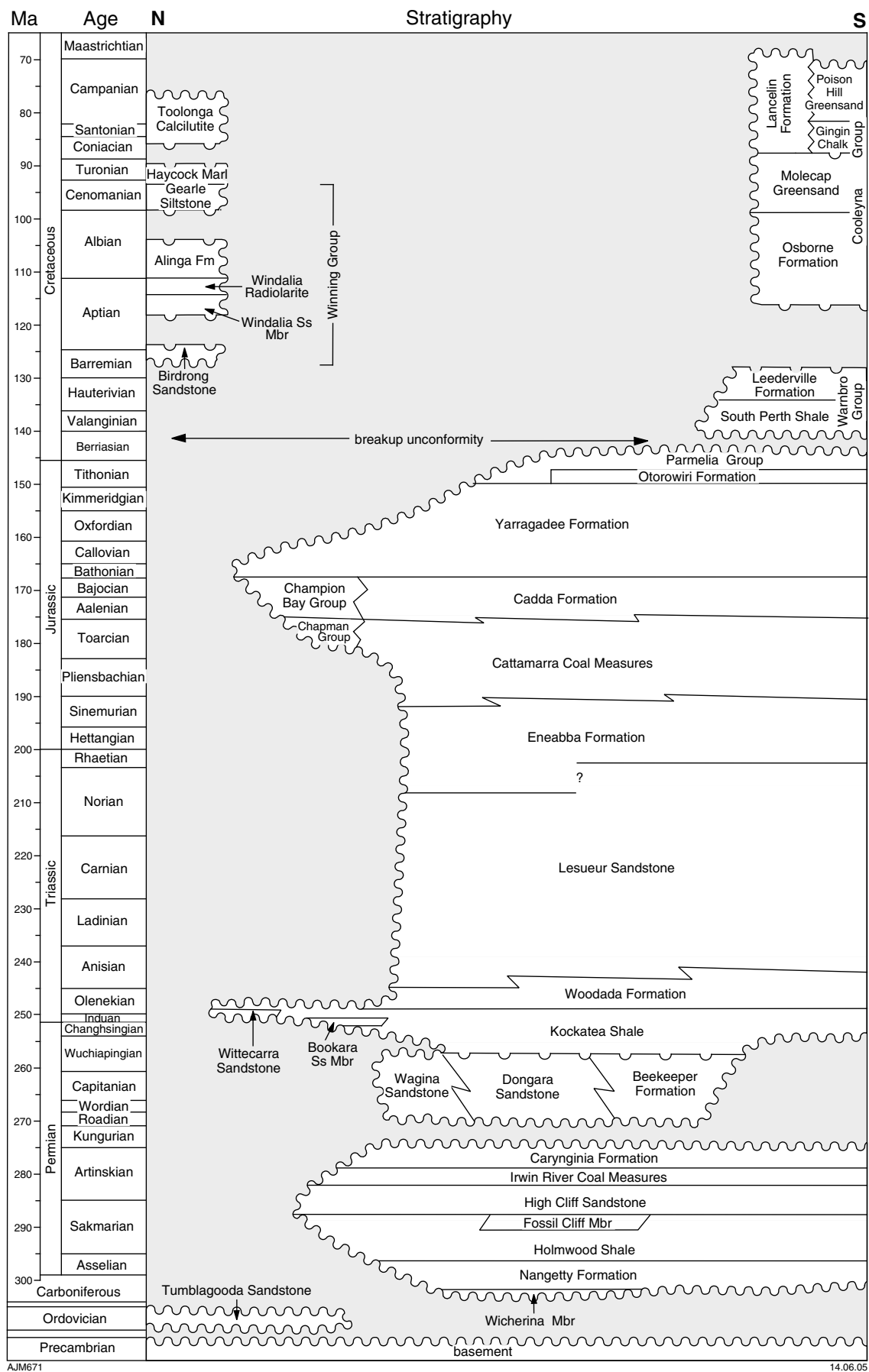


Figure 3. Pre-Cenozoic stratigraphy, northern Perth Basin, after Mory et al. (2005)

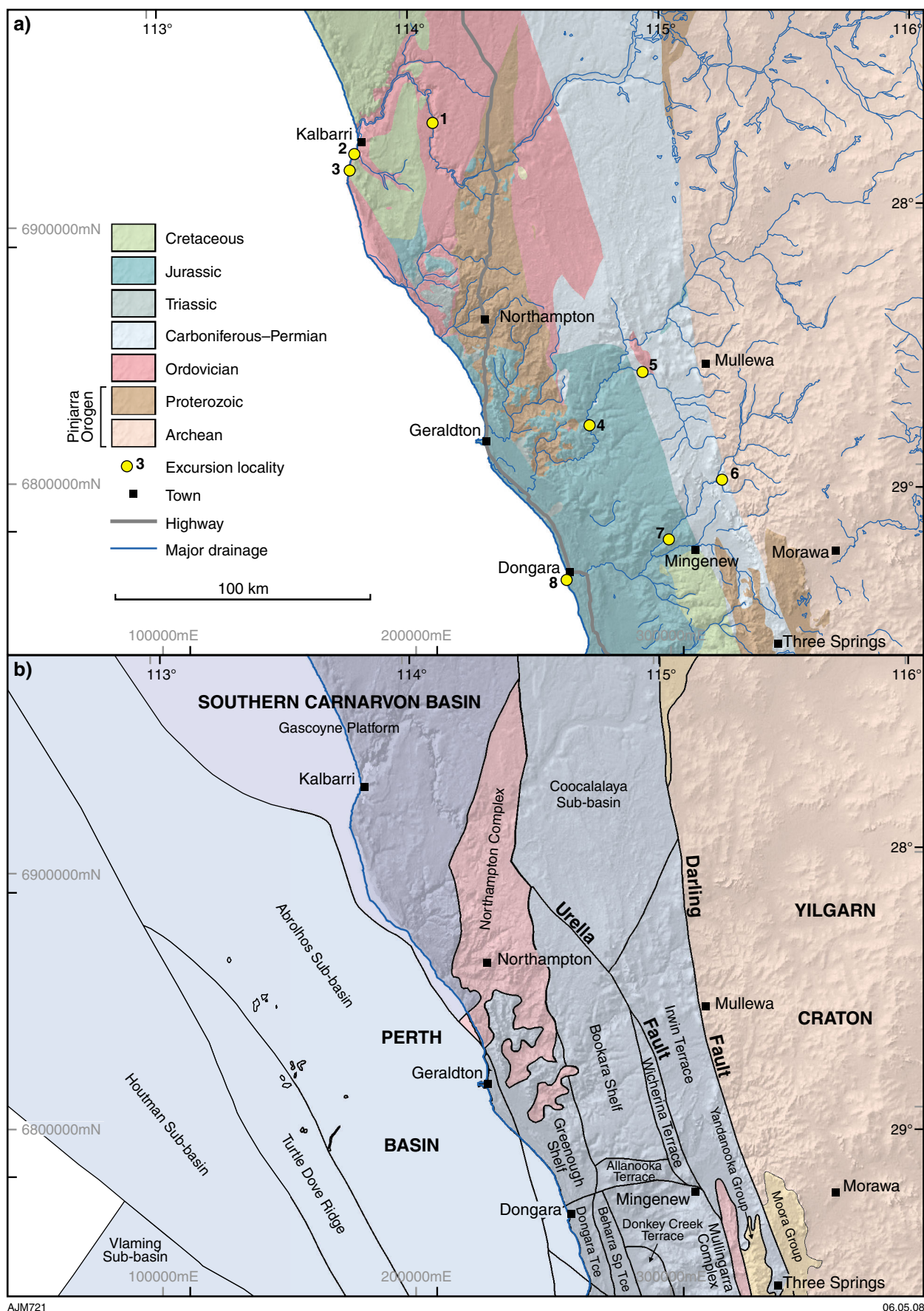


Figure 4. The northern Perth and Southern Carnarvon Basins, showing: a) excursion localities and the regional geology, superimposed over a digital elevation image from NASA SRTM data compiled by M Sandiford (<http://jaeger.earthsci.unimelb.edu.au/Images/Landform/landform.html>); b) tectonic units superimposed over the digital elevation model

Kalbarri area

Kalbarri is located 600 km north of Perth, at the southern end of the Zuytdorp Cliffs. The town is a major tourist destination, largely because of the spectacular coastal and river gorges. The area around Kalbarri is transitional between the Perth and Southern Carnarvon Basins. Triassic rocks of the Perth Basin succession extend north almost to Kalbarri, and Ordovician and Cretaceous rocks characteristic of the Carnarvon Basin succession thin towards the south and terminate south of Kalbarri.

Background geology

Ordovician and Silurian

The oldest known part of the Southern Carnarvon Basin succession is Upper Cambrian to Lower Ordovician, but is poorly known, restricted to the subsurface, and has a patchy distribution (Iasky et al., 1999, 2003). By comparison, Ordovician redbed deposition (Tumblagooda Sandstone) in braided fluvial, tidal sandflat, and nearshore to coastal, redbed settings (Hocking, 1991) covered the full extent of the Gascoyne Platform, from south of Kalbarri at least 700 km north to the Onslow area, extending into the northern Perth Basin about 150 km southeast of Kalbarri. The Ordovician basin was a north-oriented, north-opening, interior-fracture basin, which developed in equatorial to low tropical latitudes (Embleton, 1994). The western margin of the Ordovician basin is not preserved on the Australian plate.

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, with a maximum preserved thickness of about 740 m beneath Dirk Hartog Island. Environments ranged from low to relatively high energy, and salinities from (probably) normal to hypersaline. A short hiatus at the end of the Silurian was followed by deposition of mixed siliciclastic rocks and dolomite in a shallow-marine environment (Faure Formation), then sand-dominated deposition in a similar setting to that of the Late Ordovician, but with minor dolomite (Kopke Sandstone). The return of a fully marine environment led to the deposition of a mixed siliciclastic-carbonate succession (Sweeney Mia Formation), at least over the central part of the Gascoyne Platform. These three units have a maximum combined thickness of about 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 cyclical nature of Ordovician, Silurian, and Lower Devonian deposition is suggestive of a regular long-term control, perhaps mantle convection cycles (changes in spreading rates along global mid-ocean ridge systems inducing eustatic change) given the frequency of the cyclicity. Major orogenic pulses in central Australia,

influencing the central Australian basins, may also have influenced the type of deposition.

Tumblagooda Sandstone

The best exposures of the Tumblagooda Sandstone are in Kalbarri National Park, along the Murchison River gorge (the type section) and adjoining coastal gorges, where about 1300 m of fluvial to tidal sandflat redbed facies are exposed in a lightly faulted section within which dips rarely exceed 5°. These exposures were studied in detail by Hocking (1991). North of the Murchison River the Tumblagooda Sandstone is overlain by Silurian shallow-marine dolomite, limestone, and evaporites in the subsurface (e.g. Kalbarri 1, Yaringa 1). These units are also characterized by low dips, and extend across all but the easternmost part of the basin (Hocking et al., 1987; Iasky et al., 2003).

There is no internal evidence of the age of the Tumblagooda Sandstone apart from trace fossils (Trewin and McNamara, 1995), which are not particularly age diagnostic, but a lower age limit is provided by paddle impressions associated with some arthropod trackways in the middle of the unit that are indicative of eurypterids, a group that first appeared in the Arenig (Early–Middle Ordovician; McNamara, *in* Mory et al., 2003). Previous suggestions for the age of the unit ranged from middle Cambrian to Cretaceous (Hocking et al., 1987; Hocking, 1991; Iasky and Mory, 1999, table 1), of which the most constrained was the Early Ordovician age based on paleomagnetism (Schmidt and Hamilton, 1990).

The dominantly sandy facies of the Tumblagooda Sandstone imply high sediment influx, probably a function of periodic faulting along the basin margin. Terrigenous influx to the basin lessened near the end of the Ordovician, and a prolonged period of tectonic quiescence commenced allowing dominantly dolomitic deposits to accumulate in nearshore-marine to marine-shelf settings (Dirk Hartog Group, present only in the subsurface to the north of Kalbarri). Environments ranged from low to relatively high energy, and salinities from (probably) normal to hypersaline.

The type section of the Tumblagooda Sandstone in the Murchison River gorge is about 1300 m thick, and was divided into four facies associations (FA1 to FA4) by Hocking (1991). These associations outcrop in stratigraphic sequence up the type section, and delineate two fining-upward megacycles of fluvially dominated facies overlain by tidal sandflat deposits or interdistributary bay deposits (FA1 to FA2, and FA3 to FA4). Fluvial paleocurrents flowed to the northwest, with remarkably little scatter. The section at the Z Bend in the Murchison River gorge is primarily in tidal sandflat deposits (FA2), with a laterally persistent fluvial sheet near the base, towards the top of the lower couplet. The coastal cliff sections extend from the top of the upper fluvial sandstone interval (FA3) up into interdistributary bay and coastal channel deposits (FA4).

Facies Association 1 (FA1) consists of trough cross-bedded medium- to coarse-grained sandstone with unimodal,

northwestward paleocurrents. It was deposited as large, sheet-braided fluvial lobes, and grades upward into FA2. The base is not exposed.

Facies Association 2 (FA2) contains fine- to medium-grained, mostly thin-bedded sandstone, which was deposited in a very shallow marine, largely tidal, environment that became progressively more distal upsection and to the northwest. Laterally extensive, comparatively thin sheets of FA1 are interbedded in the lower part of FA2, and gradually diminish in abundance upward. The association can be explained as the product of lessening sediment influx, allowing relative transgression, or as a transgressive system gradational from FA1 and moving towards a maximum flooding surface high in FA2 prior to progradation during relative regression by FA3. Trewin (1993a,b) considered there was a strong eolian component in FA2, but this interpretation was not accepted by Hocking (2000). Adhesion surfaces and indicators of emergence are common, but eolian cross-bedding has not been recognized.

Facies Association 3 (FA3) sharply overlies FA2 and is similar to FA1, although it shows fining-upward cyclicity on a scale of 10 to 15 m. Like FA1, it was deposited in a sheet-braided fluvial environment by lobes that prograded to the northwest, although depositional energy levels were higher overall than for FA1. It can be interpreted as a highstand to regressive prograding system, where abrupt progradation over FA2 occurred in conditions of minimal accommodation.

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-upward cycles, 0.5 to 2 m thick, from medium-grained sandstone to red, commonly bioturbated, siltstone. There is a subaqueous channel complex near the top of the association, which is well exposed in the face of Red Bluff. The outcrops along the coast can be interpreted as the start of the succeeding transgressive system above the FA3 regressive system.

A fifth association (FA5), deposited as a conglomeratic alluvial fan or proximal braid-plain sequence, lies up paleoslope to the east of the Northampton Complex. Stratigraphic correlation between FA5 and the remainder of the Tumblagooda Sandstone is tentative only. Based on the abundance of *Skolithos* in both FA4 and the succession below FA5 just east of the Northampton Complex, FA5 may be the regressive system above and grading upwards out of FA4.

Triassic

In the Kalbarri region, Lower Triassic strata are exposed only in the coastal cliffs south of the town, as in the section at Shell House. They are part of the Perth Basin succession, and extend from the central part of the Perth Basin to about 200 km west-northwest of Kalbarri on the continental shelf (Iasky et al., 2003).

The Wittecarra Sandstone is disconformable on the Tumblagooda Sandstone, and consists of a basal conglomerate, overlain in turn by silty sandstone and siltstone, sandstone, conglomerate, and capped by

sandstone with probable plant rootlets. The sandstone is a braided fluvial deposit with associated soil horizons presumably derived from the uppermost Tumblagooda Sandstone. Body fossils have not been found within the Wittecarra Sandstone, but its stratigraphic position beneath the Kockatea Shale implies an Early Triassic age. The unit possibly correlates with the Bookara Sandstone Member, or with a slightly higher level, near the base of the Kockatea Shale north of Dongara.

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. Rare conchostracans within the shale in the coastal cliffs south of Kalbarri (Cockbain, 1974) are the only fossils reported from the unit near Kalbarri, and imply it is here a brackish lagoonal deposit, whereas further south near Dongara open-marine facies predominate.

Cretaceous

Cretaceous sedimentary rocks are exposed north of the Murchison River on Murchison House Station, at Meanarra Hill, and at the top of the coastal cliffs. They are considered part of the Carnarvon Basin succession, and extend less than 50 km south of Kalbarri.

The best exposures of the Winning Group (Birdrong Sandstone, Winning Sandstone Member of the Muderong Shale, Windalia Radiolarite, and Alinga Formation, in ascending order), and the Haycock Marl and Toolonga Calcilutite, are on Murchison House Station along the edge of the Pillawarra Plateau.

Only the Birdrong Sandstone, the lowermost unit in the Winning Group, is present in the coastal cliffs. It is the reservoir for many petroleum accumulations in the Northern Carnarvon Basin, and the main artesian aquifer in the Southern Carnarvon Basin.

Cenozoic

About 27 km east of Kalbarri, float of Middle to Upper Eocene siliceous marine facies deposited in the shallow inner neritic zone contains abundant sponges, molluscs, bryozoans, foraminifera, and serpulid worms (Haig and Mory, 2003).

The elevation of these marine facies (~220 m above sea level) implies a maximum age of Late Eocene for the major down-cutting of the Murchison Gorge, which Playford (2003) claimed is a response to Quaternary tectonism in the region.

The Pleistocene Tamala Limestone caps the coastal gorges, and is a calcareous eolian deposit that exceeds 300 m in thickness to the north of Kalbarri; the sea cliffs north of the Murchison River mouth are composed solely of Tamala Limestone except for rare exhumed hills of Cretaceous and Ordovician strata. At both Shell House and Red Bluff, it is less than 15 m thick, and original bedding has been largely obliterated by the development of calcrete.

Locality 1: Z Bend, Murchison River

Summary: Excellent exposures of tidal and fluvial redbed facies of the Ordovician Tumblagooda Sandstone; part of the type section.

Location: About 30 km east of Kalbarri, MGA 324900E 6938600N, KALBARRI 1:100 000 sheet. One of four public tourist lookouts and features within the river portion of Kalbarri National Park (Fig. 4).

Access: Drive east of Kalbarri to the entrance of Kalbarri National Park and follow the signs to the Z Bend. There is a walk of about 500 m from the car park to the edge of the gorge and a climb of about 50 m down to the bed of the river. Before midday is preferable for the best light on these exposures. Note that samples cannot be taken without a permit, and an admission fee to the National Park will generally apply. Care should be taken on the steep slopes and rock faces, especially below overhangs. The park is registered with the National Estate (Place ID: 9686 and 19027) partly because of its geological value. Picnic seating and toilet facilities are provided next to the car park.

Geology: The gorge in this part of the Murchison River exposes an excellent section though part of the type section of the Tumblagooda Sandstone (Fig. 5). The access road through the National Park crosses a flat plain that lies close to the unconformity surface between the Ordovician Tumblagooda Sandstone and the overlying Cretaceous succession. The main tourist lookout at the Z Bend is immediately south of a prominent joint fissure, and consists of a projecting bluff of mostly thin-bedded, tidal sandflat deposits of the Tumblagooda Sandstone. Bioturbated and rippled tidal deposits are also exposed on the walk down from the car park. From the lookout, joint control of the Murchison River course is clearly visible (Fig. 6a). A thicker bedded sheet of trough cross-bedded fluvial sandstone cuts across the thin-bedded tidal deposits between 10 and 20 m above the base of the gorge (Fig. 7). This sheet of FA1 extends both up and down the gorge at least 2 km (Fig. 8).

Another major joint fissure and gully is present about 100 m south of the lookout and ladder. At the mouth of this gully near the base of the gorge, there are two large arcing sets of eurypterid tracks, superimposed on wave ripples (Fig. 6b). Several sets of wave ripples, some wind adhesion surfaces and setulfs, can be seen between the trackways and the corner of the gorge beneath the lookout, below the level of the fluvial sheet. The fine grain size, thin bedding, and variety of bedding types are typical of the tidal deposits in the formation.

The sandstone in the lobate fluvial sheet is medium to coarse-grained, locally pebbly, poorly sorted, and trough cross-bedded. Paleocurrents were 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 facies is similar to that below, but paleocurrent directions are reversed, implying reworking by marine currents.

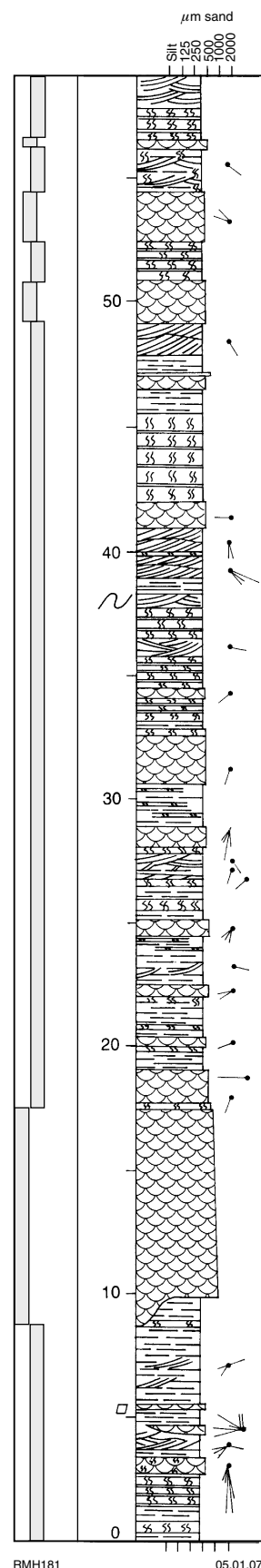


Figure 5. Measured section, the Z Bend, Kalbarri National Park, after Hocking (1991). Section line follows main fissure immediately north of lookout. Detailed sections of the fluvial interval near the base are in Figure 8



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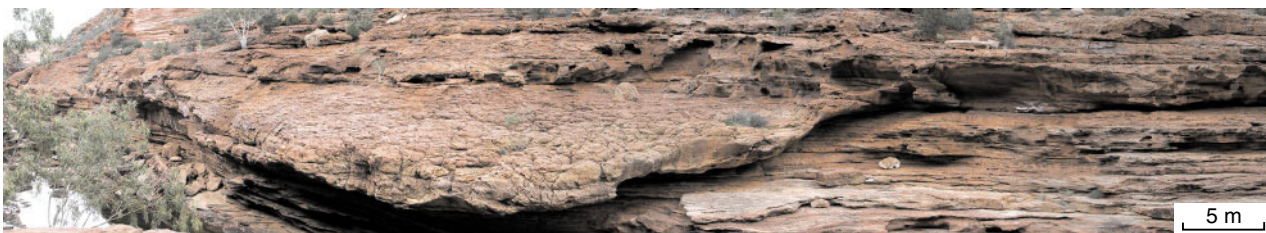
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Figure 6. Tumblagooda Sandstone, Z Bend, showing: a) joint control of the Murchison River. The asterisk marks the position of the channel shown in the section and Figure 7. Photograph taken from main lookout (MGA 249090E 6938590; b) arthropod trackways (arrowed) at the base of the Z Bend section (MGA 249075E 6938435N)

Near the base of the gorge, about 100 m downstream from the lookout, there is a northwest-trending incised channel at the base of the fluvial lobe, cutting obliquely across the gorge (Fig. 7). This is one of the few channels in the gorges; elsewhere, and above this channel, bedforms are laterally continuous, which indicates sheet braiding. Undercutting and scouring of tidal sedimentary rocks is visible at the base of the channel on the southern side (Figs 5 and 9).

Above the fluvial intercalation, there is a large, easterly facing overhang below the lookout that commonly has several seeps dripping from above it. There is a large, dewatered mound in the overhang. The main body of the mound, probably a megaripple, is white sandstone. This is capped by a red sandstone that has been disrupted and thrust-faulted on a small scale as water and sand escaped from the mound. The medium-grained sandstone also contains small ripples with granules concentrated on the crests, a feature characteristic of eolian deposition.

There is a small exposure of climbing ripples part way up the joint fissure to the lookout above the ladder, immediately left of the path. These formed in conditions of high sediment supply and are common in the tidal facies.



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Figure 7. Large channel within the Tumblagooda Sandstone, Z Bend, Murchison River (MGA 249290E 6938640N)

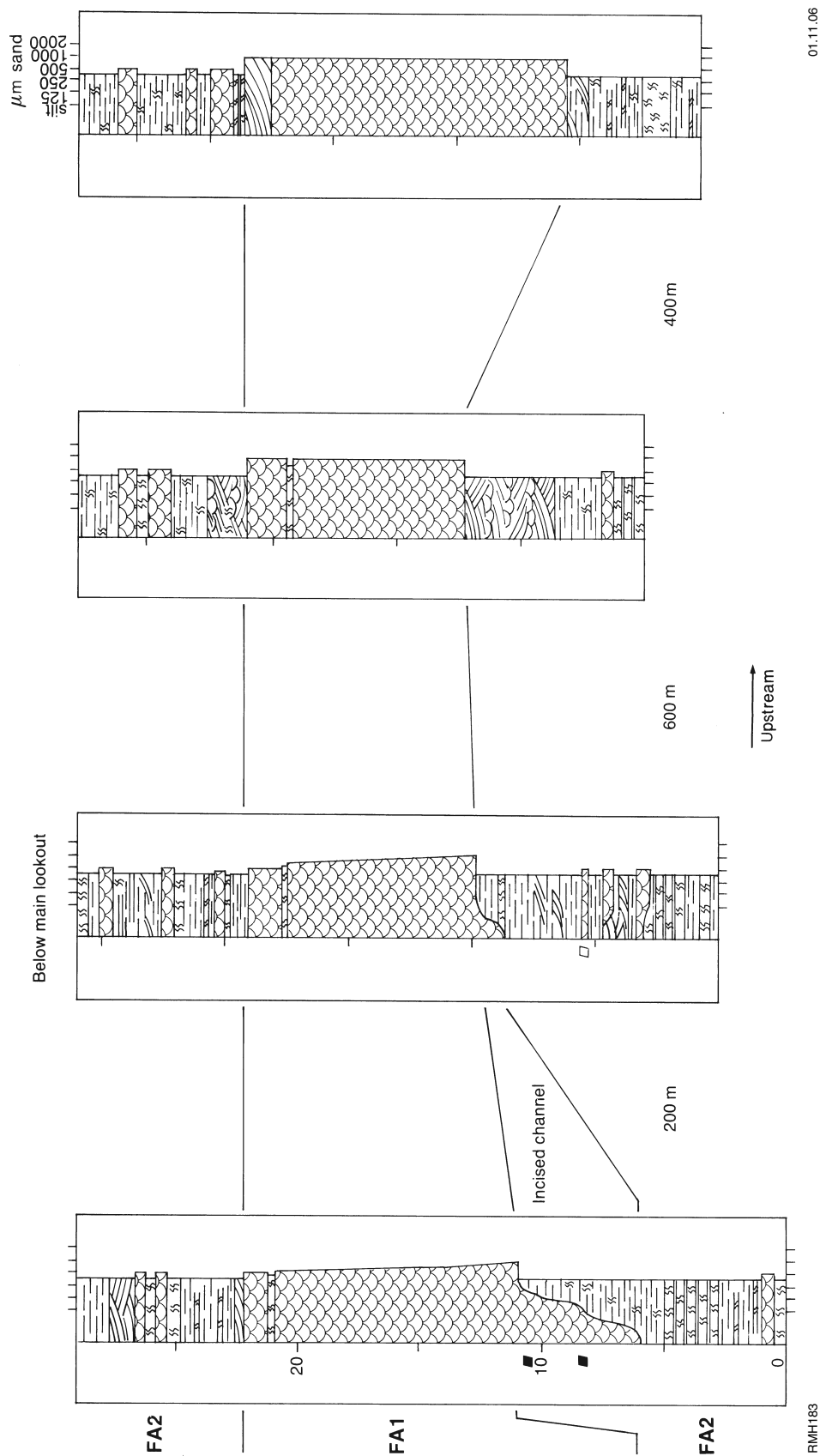


Figure 8. Detailed sections through fluvial sheet near base of Z Bend, after Hocking (1991)

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Locality 2: Red Bluff

Summary: Excellent coastal exposures of a fluvial to coastal distributary and interdistributary transition in redbed facies of the Ordovician Tumblagooda Sandstone.

Location: Four kilometres south of Kalbarri (Figs 4 and 9), MGA 218100E 6927800N, KALBARRI 1:100 000 sheet.

Access: Drive about 4 km south of the river mouth, park in the lower car park at Red Bluff beach, and walk south around the base of the cliff. Note that a permit is required to collect samples as the site is within Kalbarri National Park. Be wary of material falling from the cliff, and waves on the lower slopes. The site is best visited in the middle to late afternoon for the best lighting on the main rock faces. The site is registered with the National Estate (Place ID: 9686 and 19029).

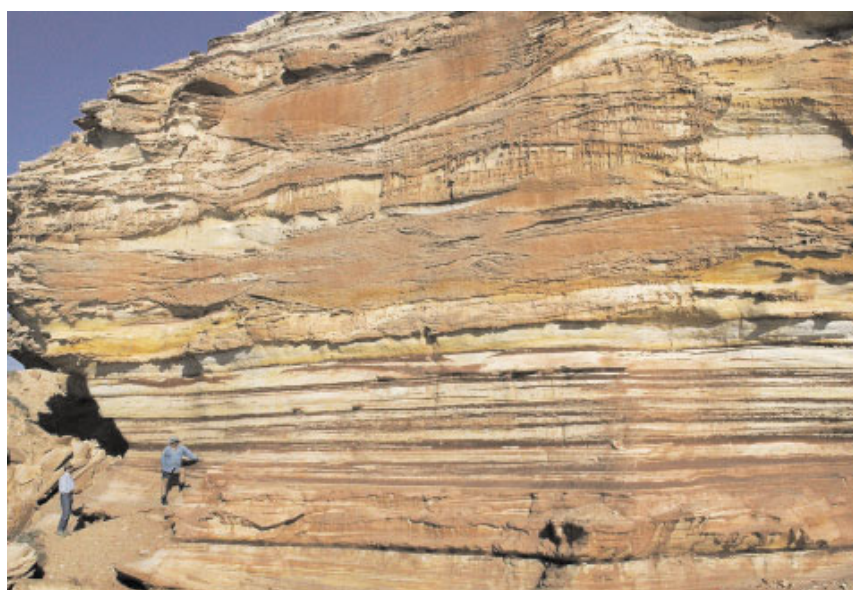
Geology: The car park at Red Bluff beach is on coarse-grained, poorly sorted, pebbly, trough cross-bedded sandstone that is stratigraphically much higher than the section at the Z Bend. The sandstone belongs to FA3, and was deposited in a coastal, high-energy sheet-braided setting. Paleocurrents were unimodal to the northwest, and very tightly clustered. Vertical burrows within the sandstone (?*Cylindricum*; Hocking, 1991), visible in some overhangs between the car park and the face of Red Bluff (Fig. 9), indicate that although fluvial processes dominated, deposition took place in a coastal setting. It is unlikely that the burrows are continental in origin, given the Tumblagooda Sandstone pre-dates all but the most primitive land plants. Sinuous trails (?*Aulichnites* or *Didymaulichus*; Hocking, 1991) are exposed in similar sandstone at Jakes Corner, about 1 km north of Red Bluff. The Gabba Gabba Member is present just below the uppermost terraces, and is well exposed directly in front

of Red Bluff. This is a distinctive pebbly sandstone to pebble conglomerate bed about 1 m thick, which extends about 40 km along the river and coastal gorges within FA3, and can be used as a stratigraphic marker. The member generally marks the lowest appearance of vertical burrows such as *Cylindricum* or *Skolithos* in FA3 (Fig. 10).

Near the top of the terraces, the fluvial FA3 facies grades up into interdistributary deposits (FA4) with the amount of red siltstone gradually increasing at the tops of the fining-upwards cycles. Immediately above the upper, wide platform, trough cross-bedded sandstone is 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 and avulsing channels, within the interdistributary setting (Fig. 11). Where bioturbated, sediments were deposited below high-tide level, and where non-bioturbated, above high tide and exposed.

A subaqueous channel sequence of *Skolithos*-bearing, cross-bedded sandstone overlies and cuts into the interdistributary sequence (Fig. 9). It is best seen from the large fallen block immediately in front of Red Bluff. Further red siltstone at the very top of the exposure suggests the abandonment, avulsion, or lateral migration of the channel sequence. Additional good exposures of this section continue 600 m south to just west of the Mushroom Rock carpark (Fig. 11). Evans et al. (in press) made a reservoir-scale study of the area between Red Bluff and Mushroom Rock to the south, using detailed measured sections and outcrop gamma logging.

Cretaceous Birdrong Sandstone and Pleistocene Tamala Limestone are present at the top of the bluff, immediately below the upper lookout on the recessive slope.



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Figure 9. Main face of Red Bluff, showing interdistributary deposits overlain by subaqueous coastal distributary. Cretaceous Birdrong Sandstone is at very top of photograph

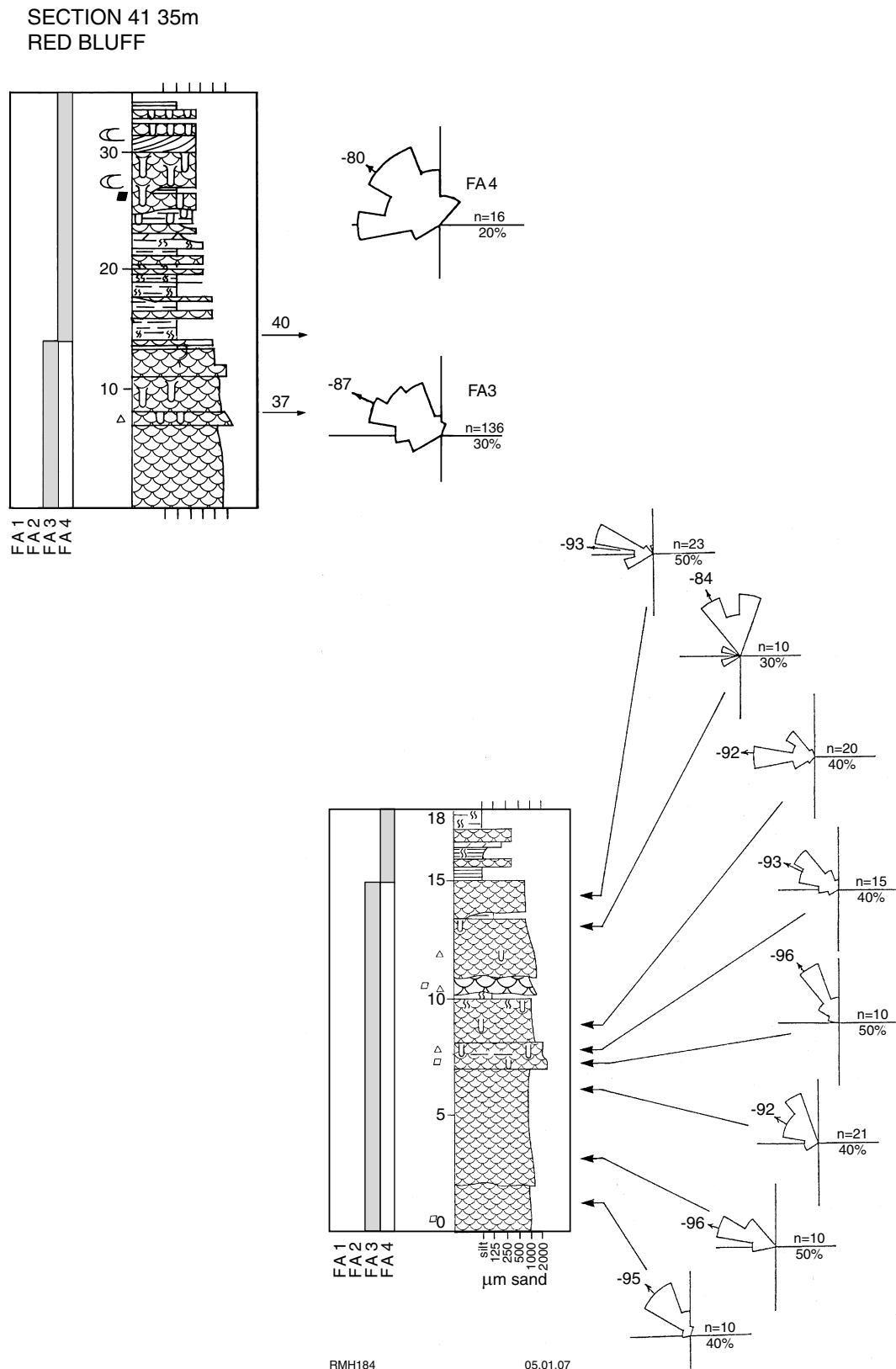
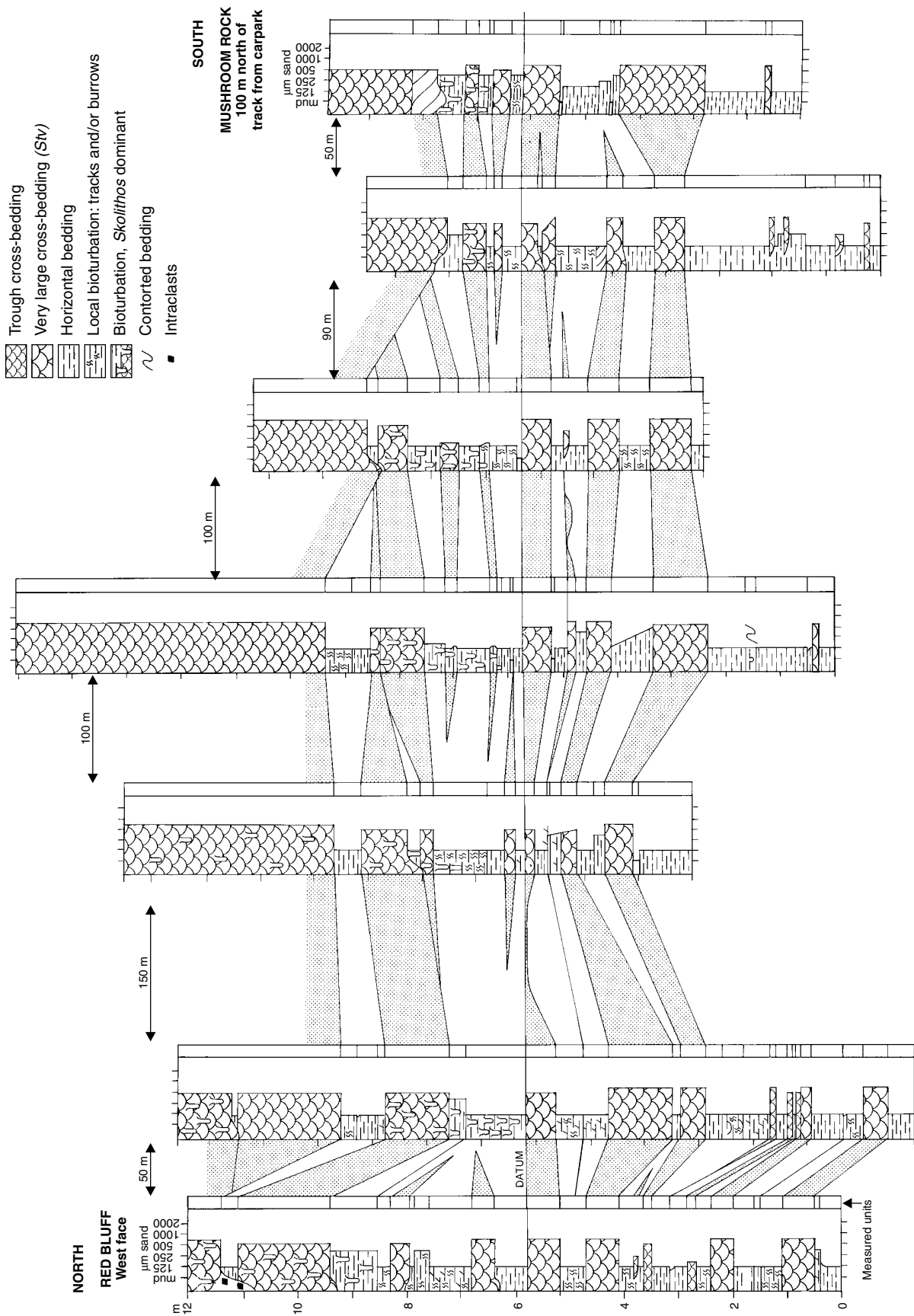


Figure 10. Measured sections of and in front of main face at Red Bluff, after Hocking (1991). The lower section is a more detailed version of the upper, showing development of bioturbation above Gabba Gabba Member (at 8 m), and paleocurrent variation



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Figure 11. Measured sections through the Tumblagooda Sandstone, Red Bluff (MGA 218030E 6927700N) to Mushroom Rock (MGA 217950E 6927060N); after Hocking (1991)

Locality 3: Shell House

Summary: Excellent exposures of fluvial to tidal redbed facies of the Ordovician Tumblagooda Sandstone, disconformably overlain by fluvial Lower Triassic Wittecarra Sandstone (type section) and shallow-marine Kockatea Shale, are preserved in a small graben draped by the Lower Cretaceous Birdrong Sandstone and Pleistocene Tamala Limestone.

Location: About 11 km south of Kalbarri (Fig. 4), MGA 215900E 6921500N, KALBARRI 1:100 000 sheet.

Access: Drive 10 km south of the river mouth, turn southwest into Natural Bridge Road and then northwest after 1.6 km to Shell House. Walk down the spur immediately north of the car park to near the top of the Tumblagooda Sandstone, and then a further 300 m to the northeast. Note that a permit is required to collect samples as the site is within Kalbarri National Park. Take care on the steep scree slopes and rock surfaces. The site is best visited in mid-afternoon for the best lighting on the main rock faces. The site is registered with the National Estate (Place ID: 9686 and 19029).

Geology: Shell House (Fig. 12) is one of the few localities where it is possible to climb down to sea level in the coastal cliffs south of Red Bluff. The Tumblagooda Sandstone at Shell House is a fluvial and interdistributary bay sequence, similar to that at Red Bluff. A small graben is present in the centre spur (Fig. 13). The southern and northern spurs are at approximately the same structural level, and the northern fault can be seen in the gully between the central and northern spurs (Figs 12a and 13). Uppermost *Skolithos*-bearing sandstone beds are the best indicators of the top of the Ordovician section (Fig. 12b). In the Tumblagooda Sandstone, the Gabba Gabba Member — a distinct pebbly sandstone — and the first appearance of *Skolithos* above a distinct red interval, allow reasonably precise determinations of the fault throws. Triassic strata are present only in the graben over the central spur. The Lower Cretaceous Birdrong Sandstone forms a blanket over the graben, which indicates that the structure formed between the Early Triassic and the Early Cretaceous. The Wittecarra Sandstone and Kockatea Shale are best exposed on the south side of the central spur (Figs 12a–c). Although the Wittecarra Sandstone is texturally similar to the underlying Tumblagooda Sandstone, from which it was undoubtedly derived, there is an erosional contact and a distinct change to a mottled character in the younger unit. The section is the northernmost known accessible outcrop of Perth Basin units on the coast.

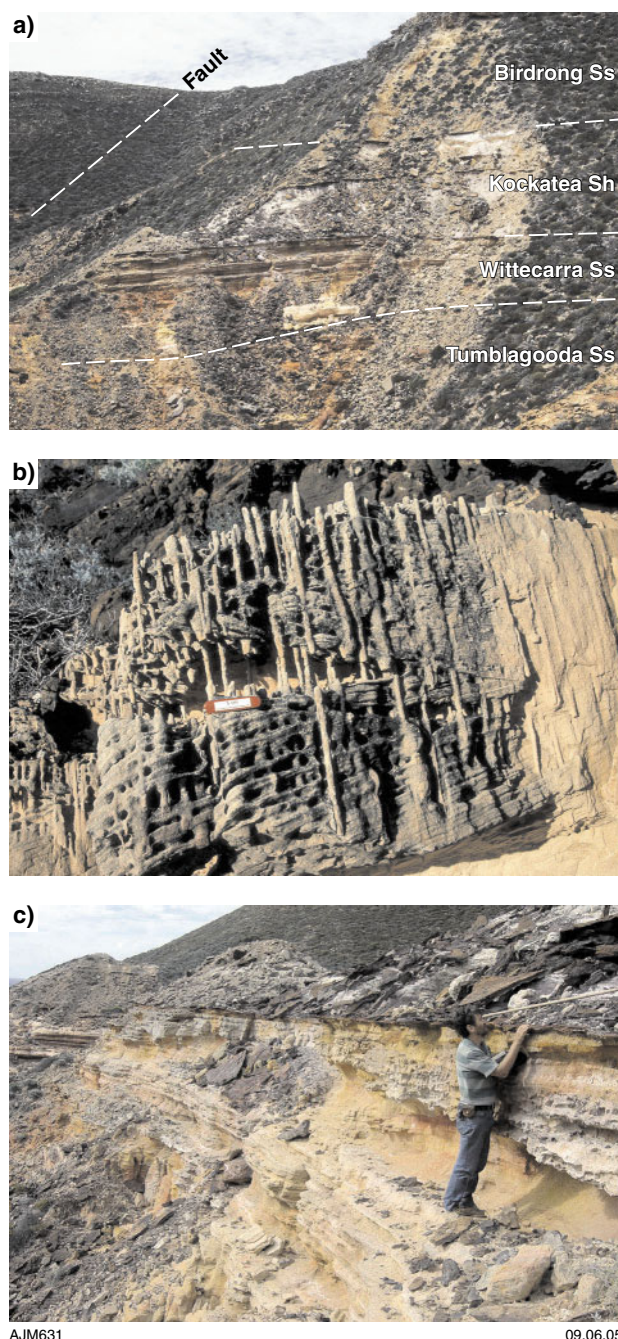


Figure 12. Shell House: a) Cretaceous and Triassic rocks overlying the Ordovician Tumblagooda Sandstone (MGA 216180E 6921500N); b) *Skolithos* bed in Tumblagooda Sandstone (MGA 216120E 6921680N); c) top of the type section of the Wittecarra Sandstone (MGA 216150E 6921600N). Contact with Kockatea Shale is level with person's head. Photograph courtesy of Richard Evans, Curtin University, Perth

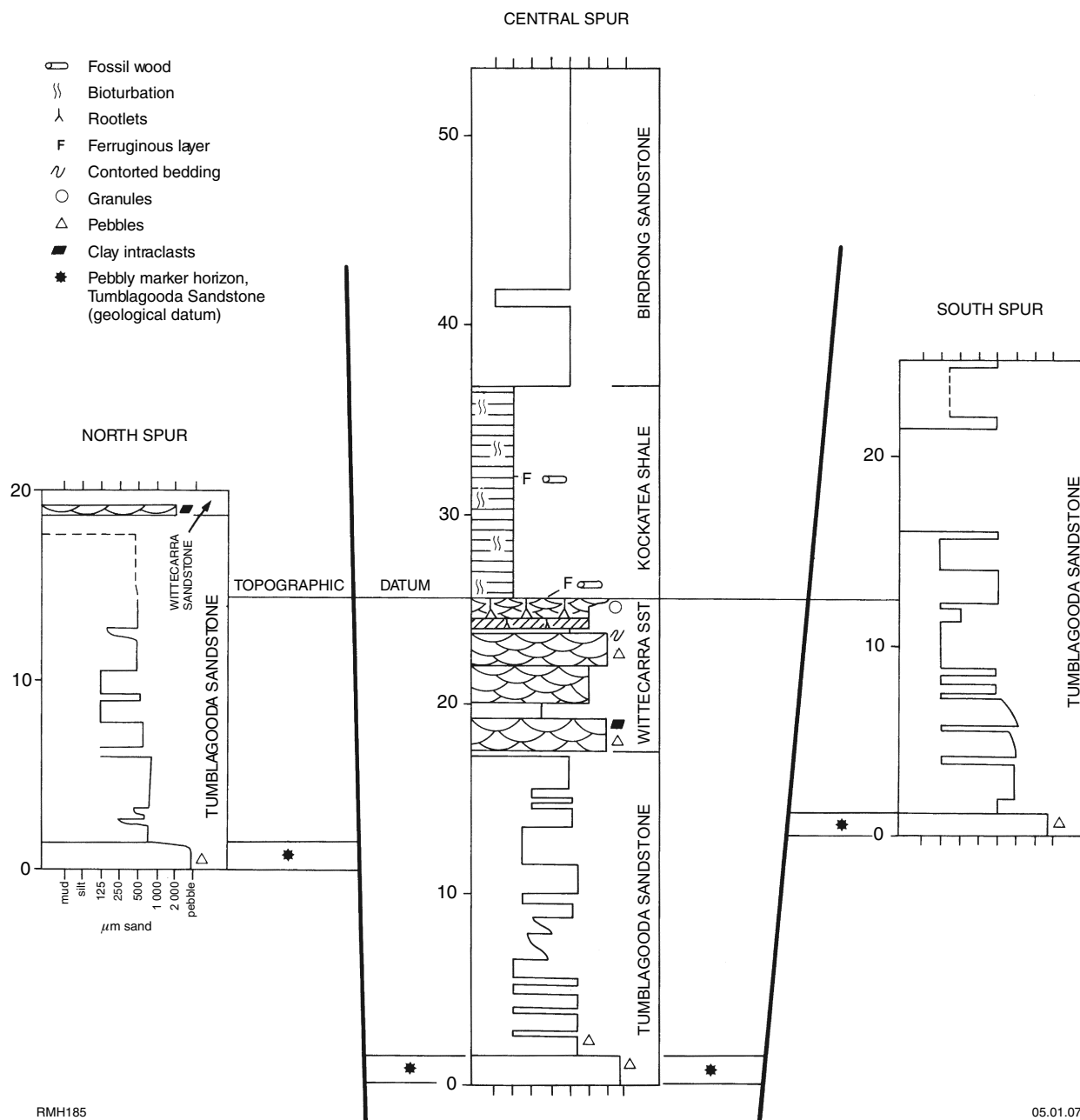


Figure 13. Measured sections showing the small graben at Shell House, after Hocking (1991; MGA 216180E 6921500N to 216180E 6921750N)

Geraldton area

Background geology

Flat-lying Lower Triassic and Lower to Middle Jurassic strata onlap gneiss of the Northampton Complex. The southernmost known exposures of the Ordovician Tumblagooda Sandstone are north of Wicherina on the eastern margin of the Northampton Complex.

Triassic

The only Triassic unit that outcrops in the Geraldton area is the Lower Triassic Kockatea Shale. Overall, exposures are poor, as is typical of shaly rocks, so sandier intervals of the formation are commonly better represented in outcrop. The unit is disconformably overlain by sandstone of the Lower Jurassic Chapman Group whereas further south, in the subsurface near Dongara, deposition appears to have continued without a significant break until the end of the Jurassic. The light colouration of palynomorphs from the Kockatea Shale near Geraldton implies a hiatus in deposition rather than significant erosion at this level.

Jurassic

Jurassic strata onlap both the Triassic Kockatea Shale and Precambrian basement. The succession below the Upper Jurassic Yarragadee Formation, which PE Playford (1959) divided into two groups (Chapman and Champion Bay Groups), is laterally equivalent to the upper part of the Cattamarra Coal Measures and the Cadda Formation further south in the basin. The lower unit, the Chapman Group, consists of two dominantly sandstone units: the Greenough Sandstone is described as multicoloured, poorly sorted and bedded, and medium to coarse grained with minor conglomerate and claystone, whereas the overlying Moonyoonooka Sandstone is very fine grained and feldspathic with minor carbonaceous shale and conglomerate. Both units have their type sections on the Moonyoonooka property east of Geraldton. The overlying Champion Bay Group records a short-lived marine transgression within otherwise dominantly fluvial facies in the Jurassic. The best-exposed section is in Bringo rail cutting (described below) where all four formations (Colalura Sandstone, Bringo Shale, Newmarracarra Limestone and Kojarena Sandstone) are present. Of these units, the Newmarracarra Limestone is the most fossiliferous, and was first reported in one of the earliest fossil descriptions from Western Australia (Clarke, 1867). McNamara and Brimmell (1992) illustrates many of the macrofossils from this unit.

Locality 4: Eradu

Summary: Low road cutting showing bioturbated fluvial facies of the Upper Jurassic Yarragadee Sandstone.

Location: Road cutting about 43 km east of Geraldton (Fig. 4), MGA 308730E 6823175N, INDARRA 1:100 000 sheet.

Access: On Eradu Road North, about 1 km north of the Geraldton – Mount Magnet Road or 900 m south of the rail crossing. Note that no public facilities are available at this settlement.

Geology: The road cutting at Eradu is in an intensely bioturbated fine-grained sandstone with overlying broad scour troughs. A 40 cm-wide and 1.5 m-high vertical feature eroded by the uppermost bed in the cutting (Fig. 14a) has been variously interpreted as a cast of a tree root or a giant burrow, but bioturbation near the feature (Fig. 14b) is most likely to be due to the activity of lateral roots. This outcrop was mapped as Yarragadee Formation (Playford et al., 1970), but similar bioturbated sandstone 1 km to the north-northwest on the west bank of the Greenough River is shown as Upper Permian Wagina Sandstone. Assignment of both outcrops to the Yarragadee Formation is supported by the presence of Jurassic palynomorphs in the interval 3–40 m in Calyx Bore 5, 1 km to the north (Swarbrick, 1964; section originally described by Blatchford, 1930).

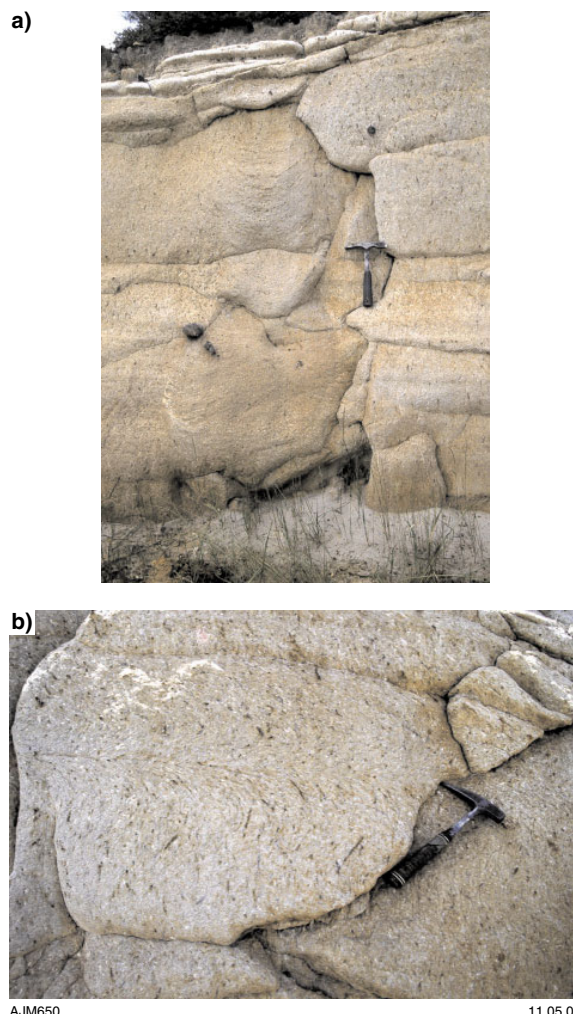


Figure 14. Road cutting in Yarragadee Formation, Eradu (MGA 308730E 6823175N): a) possible tree cast; b) bioturbation

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Mullewa area

Background geology

The Carboniferous–Permian Nangetty Formation dominates exposures between the Darling and Urella Faults in the Mullewa area. Excellent outcrops of diamictite facies are exposed along Wenmillia Creek and Wooderarrung River adjacent to the Darling Fault. Similar diamictites further south along the Irwin River, also with a gritty sandy mudstone matrix, were informally termed ‘conglomeratic argillite’ by Le Blanc Smith and Mory (1995). Massive facies predominate but crude horizontal stratification, rafts of deformed sandstone, and conglomerate are common. Clasts are rounded to angular, up to several metres in diameter with no preferred long axis orientation, and are commonly faceted and striated. They include mixtures of local and extrabasinal types — most are granite from the Yilgarn Craton, and Proterozoic dolomite and quartzite derived from the Moora–Watheroo area 100–150 km to the south (Glover, 1974; Playford et al., 1976; Le Blanc Smith and Mory, 1995) indicating northerly flow of ice. Diamictite facies are interbedded with highly deformed fine- to medium-grained sandstones that are complexly folded with abundant dish and dewatering structures; remnants of original structure suggest that these sandstones were probably graded, horizontally laminated, and rippled. The diamictite–sandstone–mudstone facies association is interpreted as the product principally of subaqueous sediment gravity-flows that ranged from debris flows (diamictites) to coarse- and fine-grained turbidites (sandstone and laminated mudstone; Eyles et al., in prep.). The large number of striated and faceted clasts within this association clearly indicates a nearby glacial source of the sediment. Grading and stratification within diamictite, together with rafts of sandstone and conglomerate, indicate that coarser grained and better-sorted facies were only partially assimilated and homogenized during down-slope debris flow. Eyles et al. (in prep.) explains such poorly sorted debris flows as the product of mixing of pre-existing sediments during down-slope slumping and flow.

Massive, rippled, contorted, and pebbly sandstone facies predominate in the Nangetty Formation in this area, and probably belong within the Wicherina Member of Mory and Iasky (1996). The only palaeontological evidence for the age of the formation in the area is from shallow bores north of the Greenough River, from which Backhouse (1998) recovered Middle to Late Carboniferous and Early Permian palynomorphs.

The only other significant unit in the area is a fluvial cross-bedded pebbly sandstone facies near Noondamurra Pool, north of Bindoo Spring, that has been assigned to the Tumblagooda Sandstone by Playford et al. (1976) and to an unnamed Devonian unit by Hocking (1991). Permian and Jurassic outcrops west of the Urella Fault are poor, as are exposures along the fault zone. The Darling Fault is moderately well exposed in Wenmillia Creek and upstream from its junction with the Wooderarrung River.

Locality 5: Kockatea Gully

Summary: Low, extensive exposure along gully of glacio-marine facies of the ?mid-Carboniferous to Lower Permian Nangetty Formation, with numerous dropstones.

Location: About 25 km west of Mullewa (Fig. 4), MGA 329350E 6839915N, INDARRA 1:100 000 sheet.

Access: Walk west into gully about 300 m south of the junction of Brenkley Road with Tenindewa Road. Contact K Weir (c/- PO Tenindewa, WA 6632, or phone (08) 9962 5032) for access.

Geology: The low exposures of Nangetty Formation in this creek consist mainly of tillite with a crudely bedded silty matrix and common erratic boulders of diverse origins. The boulders are up to 1 m in diameter and most are still embedded in the matrix (Fig. 15). Faceting and striations are best developed on siltstone boulders. The position of this site within the Nangetty Formation is unclear. The exposures could be either Carboniferous or Permian in age.



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Figure 15. Glacial deposit, Nangetty Formation, Kockatea Gully (MGA 329350E 6839915N)

Mingenew area

Background geology

Permian

Permian sedimentary rocks form well-known exposures in the northern part of the Perth Basin between the Darling and Urella Faults, and are widespread in the subsurface throughout the remainder of the basin. The succession comprises mixed marine and continental deposits that locally probably reach thicknesses in excess of 2600 m (Playford et al., 1976) and typically rest unconformably on Precambrian metamorphic and plutonic rocks, and on Ordovician, and ?Devonian strata in the north. In the southern Perth Basin, by comparison, the Permian succession is represented entirely by continental deposits (Stockton and Sue Groups; Le Blanc Smith and Kristensen, 1998).

The best exposures of Permian rocks are in the Irwin River and Woolaga Creek areas but there are also scattered outcrops along the Lockier, Greenough, and Murchison river valleys. Coalseam Conservation Park (Locality 6), at the junction of the north and south branches of the Irwin River (Figs 16–21), contains the most accessible Permian exposures. The Gregory brothers first discovered coal in the State along the South Branch of the Irwin River in 1846, and Gregory (1861) made the first brief geological description of the area. The Lower Permian succession consists of glaciogene deposits (Nangetty Formation and Holmwood Shale), locally capped by cold-water, richly fossiliferous shallow-marine carbonates (Fossil Cliff Member of the Holmwood Shale), overlain in turn by siliciclastic paralic deposits (High Cliff Sandstone), fluvial-deltaic facies (Irwin River Coal Measures), and restricted marine facies (Carynginia Formation). Upper Permian fluvial deposits (Wagina Sandstone) overlie the Carynginia Formation with a markedly erosive base. There is little evidence of an angular unconformity in outcrop but seismic profiles show a distinctly angular relationship offshore (Smith and Cowley, 1987). Fossiliferous marine facies of the Mingene Formation appear to be laterally equivalent to the lower part of the Carynginia Formation but are known only from a few outcrops near Mingene.

Nangetty Formation

The Nangetty Formation consists of shale, sandstone, conglomerate, and minor tillite, and extends through much of the northern Perth Basin. Thicknesses exceed 1500 m adjacent to the Urella Fault, but the unit pinches out against the Northampton Complex to the northwest and is absent west of the complex. Erratic boulders (commonly faceted and striated) up to 6 m in diameter within the formation indicate glacial activity and ice rafting of dropstones. The unit unconformably overlies Precambrian metamorphic and plutonic rocks that resemble many of the erratic boulders in the formation, and locally the Ordovician Tumblagooda Sandstone and ?Devonian strata.

The formation was probably deposited in both marine and continental environments and typically contains

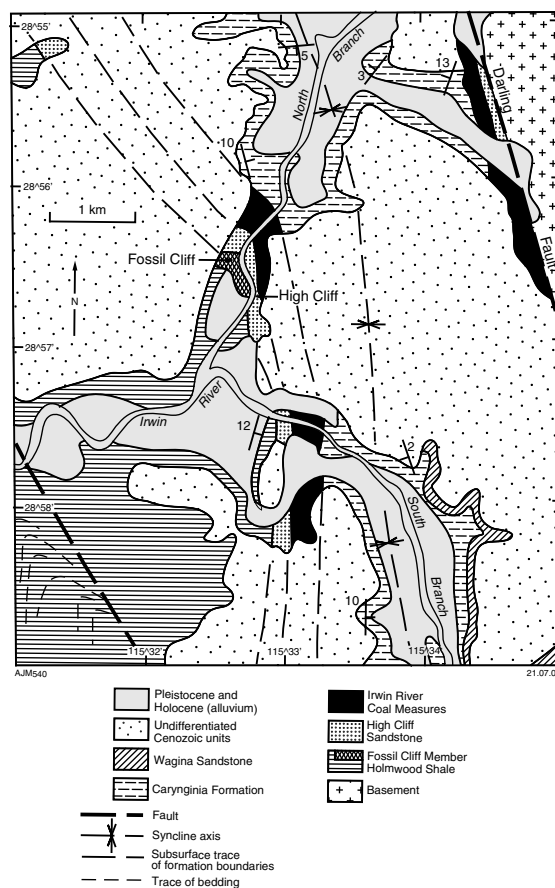


Figure 16. Simplified geological map of the junction of the North and South Branches of the Irwin River (after Clarke et al., 1951; Le Blanc Smith and Mory, 1995)

Asselian–Sakmarian palynomorphs. Middle to Late Carboniferous palynomorphs are also in the unit north of the Greenough River. Exposures are typically poor, even in Nangetty Hills, the type area of the unit. Although a specific type section has not been proposed there are reasonable, but discontinuous, nearby exposures along the Irwin River (between MGA 348300E 6783400N and MGA 351300E 6791400N). The largest glacial erratic is the quartzitic ‘White Horse’, on ‘Mungaterra’ (MGA 352120E 6787280N) derived from the Coomberdale Chert near Moora.

Holmwood Shale

The Holmwood Shale was originally proposed for the dark shale conformably overlying the Nangetty Formation and conformably underlying the ‘Fossil Cliff Formation’ (Clarke et al., 1951). Its type section is along Beckett Gully 8 km south of Coalseam Conservation Park. Johnson et al. (1954) and Playford et al. (1976) noted that the richly fossiliferous calcareous facies attributed to the Fossil Cliff Member was thin, lenticular and difficult to map, and redefined these beds as an uppermost member. The Woolaga Limestone Member and the Beckett Member

represent additional lenticular calcareous facies lower in the Holmwood Shale, but also do not extend far beyond the areas after which they are named.

The Holmwood Shale comprises a thick (about 450 m) section of grey–green shale and thin limestone beds in the lower part passing transitionally into grey–black micaceous, jarositic, and gypsiferous shale and siltstone with minor discontinuous beds of cross-laminated fine-grained sandstone and coquinite in the upper part. Dropstones in situ are rare within the formation. The shale and siltstone facies are poorly fossiliferous, commonly only containing cryptostomate bryozoans. In contrast, the limestone facies are richly fossiliferous. Palynological and invertebrate faunal assemblages indicate a Sakmarian age (Segroves, 1971; Playford et al., 1976). Lithologies, sedimentary structures, and fossils representative of this formation reflect chiefly cold-water low-energy marine depositional environments. Fossiliferous limestone lenses probably represent localized well-aerated shallow-marine banks.

Fossil Cliff Member

The type section of the Fossil Cliff Member is best exposed at Fossil Cliff, on the North Branch of the Irwin River, immediately upstream from High Cliff. The member consists of interbedded dark micaceous and gypsiferous siltstone, sandy siltstone, shale, and bioclastic calcarenite deposited in a series of coarsening-upward parasequences (Fig. 17). The carbonate beds are markedly lenticular and the member outcrops sporadically between Fossil Cliff and a point 16 km to the south. The skeletal component of the limestone beds is diverse though fragmentary, whereas the siltstones host less-diverse macrofaunas preserved mostly as moulds. Changes in lithology and fossil content are attributed to sea-level fluctuations as well as the change from high terrigenous to impoverished terrigenous input (Ferdinando, 2002).

The age of the Fossil Cliff Member is regarded as Sakmarian (either late Tastubian or Sterlitamakian) based on a single specimen of the ammonoid *Metalegoceras kayi* from the type section (Glenister et al., 1973).

High Cliff Sandstone

Clarke et al. (1951) defined this formation for the interbedded sandstone, conglomerate, and siltstone transitional between the 'Fossil Cliff Formation' and the Irwin River Coal Measures. Both lower and upper contacts are conformable. The 24 m-thick type section (Fig. 18) is at High Cliff on the North Branch of the Irwin River (Playford et al., 1976). Clarke et al. (1951) and Sanders and Ingram (1964) listed thicknesses of about 37 and 26 m, respectively, for this section. The discrepancies appear to relate to positioning of the formation's upper boundary, here taken to be at the base of a thick dark shale and siltstone bed in the upper part of High Cliff. No coal is exposed in High Cliff and the lenticular character of many beds inhibits ready correlation with the coal-bearing section 500 m upstream. The High Cliff Sandstone and Irwin River Coal Measures are often difficult to distinguish in the subsurface where core is not

available, but collectively these formations are recognized throughout the northern Perth Basin.

Body fossils are absent from the formation at High Cliff although both high energy (*Skolithos*-type) and low energy (*Planolites*- and *Rosselia*-type) burrow forms are abundant (Fig. 22a). A marine fauna including bivalves, gastropods, and brachiopods has been recorded from Woolaga Creek, 27 km south of the type section. The invertebrate faunas, trace fossil assemblages, local hummocky cross stratification, wave ripples, and sporadic conglomeratic lenses (including dropstones, Fig. 22b) suggest deposition in shallow-marine to shoreface environments. The faunal and palynomorph assemblages indicate an Artinskian age for this unit (Segroves, 1971; Playford et al., 1976).

Irwin River Coal Measures

Clarke et al. (1951) introduced this name for the coal-bearing section along the North Branch of the Irwin River (Fig. 22c) that lies conformably between paralic strata of the High Cliff Sandstone below and marine siltstone of the Carynginia Formation above. The formation is about 66 m thick in the type section and about 76 m thick at Woolaga Creek (Le Blanc Smith and Mory, 1995) but reaches 288 m in the subsurface west of the Urella Fault.

The formation consists of a mixed succession of sandstone, siltstone, carbonaceous shale, and coal (Fig. 22c,d). Although previously regarded as fluvial (McIntosh, 1980), the unit is here interpreted to represent various delta plain depositional environments (Fig. 18). Palynological studies suggest an Artinskian age for this unit (Balme in McWhae et al., 1958; Segroves, 1971).

Animal fossils have not yet been recorded from the unit although invertebrate burrows are locally common (Fig. 19). The unit contains an abundant, but typically low diversity, Early Permian Gondwanan flora incorporating species of *Glossopteris*, *Vertebraria*, *Gangamopteris*, *Sphenophyllum*, *Neomariopteris*, *Paracalamites*, *Lelstotheca*, and *Gondwanaphyton* (in decreasing order of abundance). The floras contain a greater proportion of herbaceous plants compared to the gymnosperm-dominated coeval floras of the Collie Basin coal measures south of Perth. Floral differences can be attributed to deltaic versus fluvial plain depositional settings for these respective coal measures. Plant fossils are most visible in the shale bed immediately above the fourth (highest) coal seam in the North Branch of the Irwin River.

Four principal coal seams are represented in the North Branch of the Irwin River. Several test drives were opened into the seams during the late 19th Century and again in the 1940s but seam splits, discontinuities, and relatively high ash and sulfur contents discouraged further exploration until the 1980s when shallow drilling found nine seams south of the Irwin River exposures. The thickest known seam reaches 8 m in the Lockier Deposit, 12 km south of the outcrops on the South Branch of the Irwin River, where the cumulative coal thickness is 14 m (Le Blanc Smith and Mory, 1995). Facies changes in the

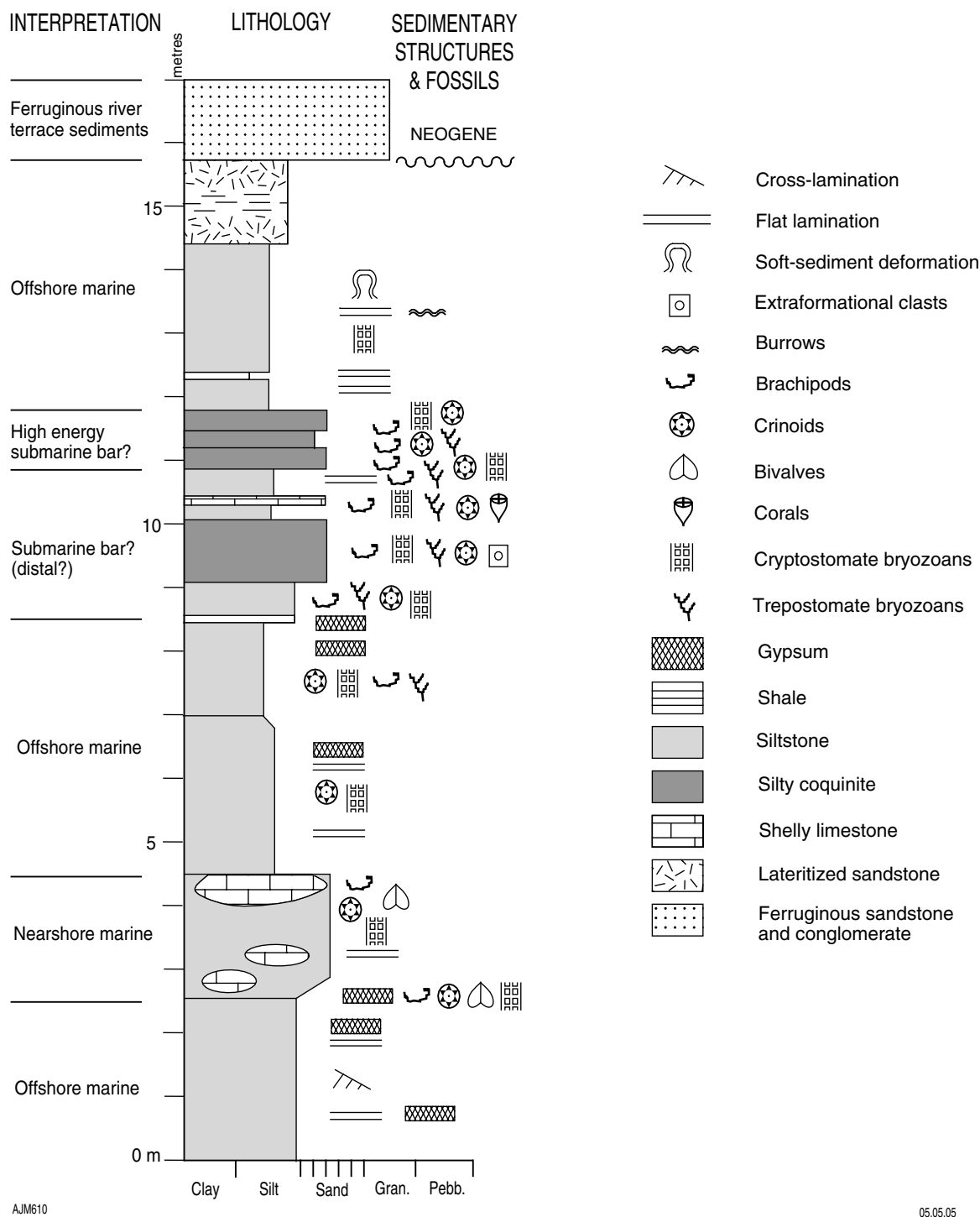


Figure 17. Measured section, Fossil Cliff, Irwin River (MGA 357785E 6789390N; after McLoughlin in Haig et al., 1991)

coals, and other lithologies, hinder subsurface correlations and resource estimates from the existing data, and are a function of the rapidly changing depositional environments of a deltaic setting.

Carynginia Formation

The type section of the Carynginia Formation (amended from 'Carynginia Shale' of Clarke et al., 1951 by

Playford and Willmott, in McWhae et al., 1958) is in Carynginia Gully, a tributary of the North Branch of the Irwin River. As these exposures are poor, Playford and Willmott (in McWhae et al., 1958) proposed Woolaga Creek, 27 km south of Coalseam Conservation Park, as the chief reference section. The formation extends throughout the subsurface of much of the northern Perth Basin and consists of black to grey micaceous jarositic shale and siltstone with lesser interbedded sandstone and

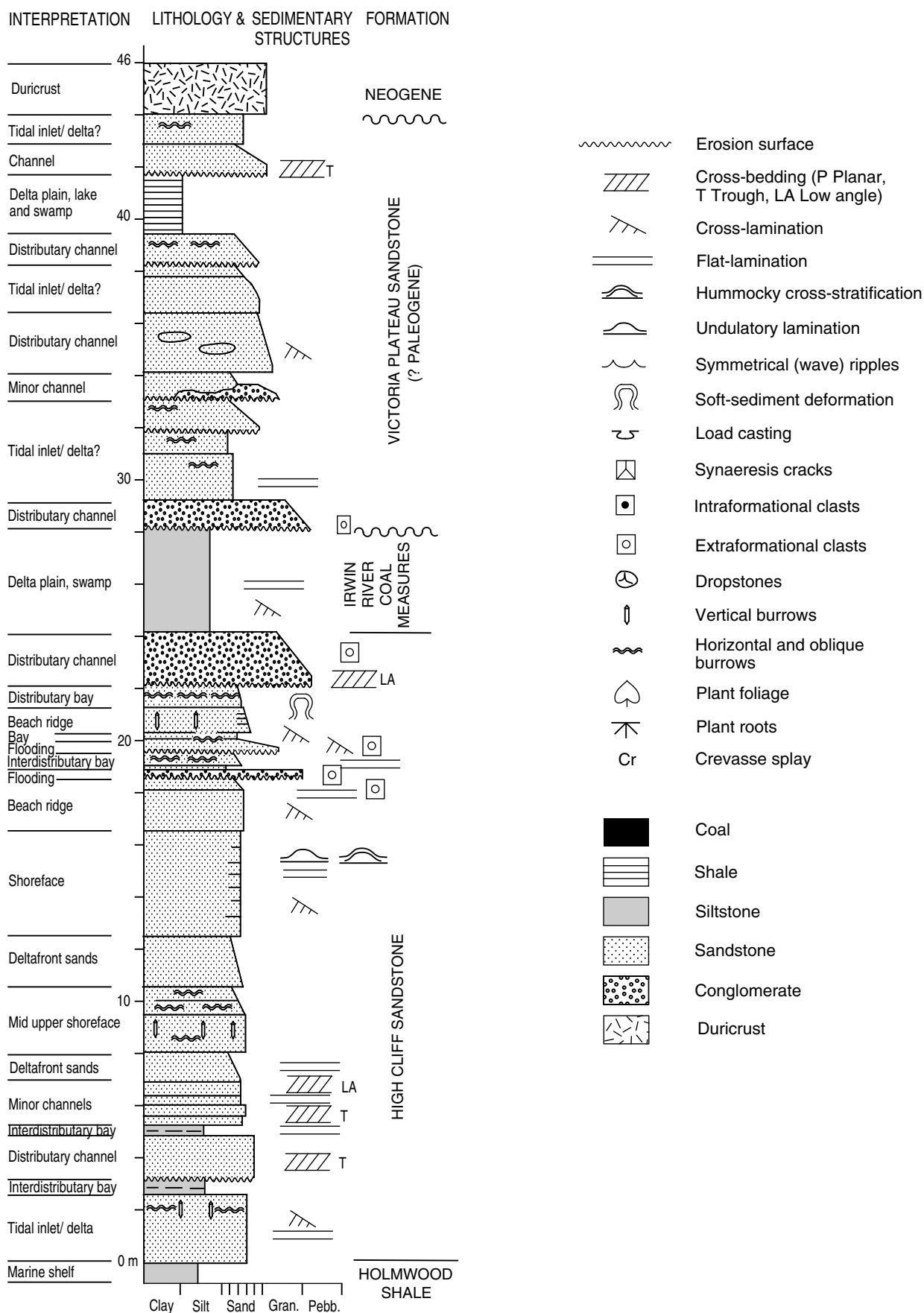


Figure 18. Measured section, High Cliff, Irwin River (MGA 358580E 6797235N; modified after McLoughlin in Haig et al., 1991)

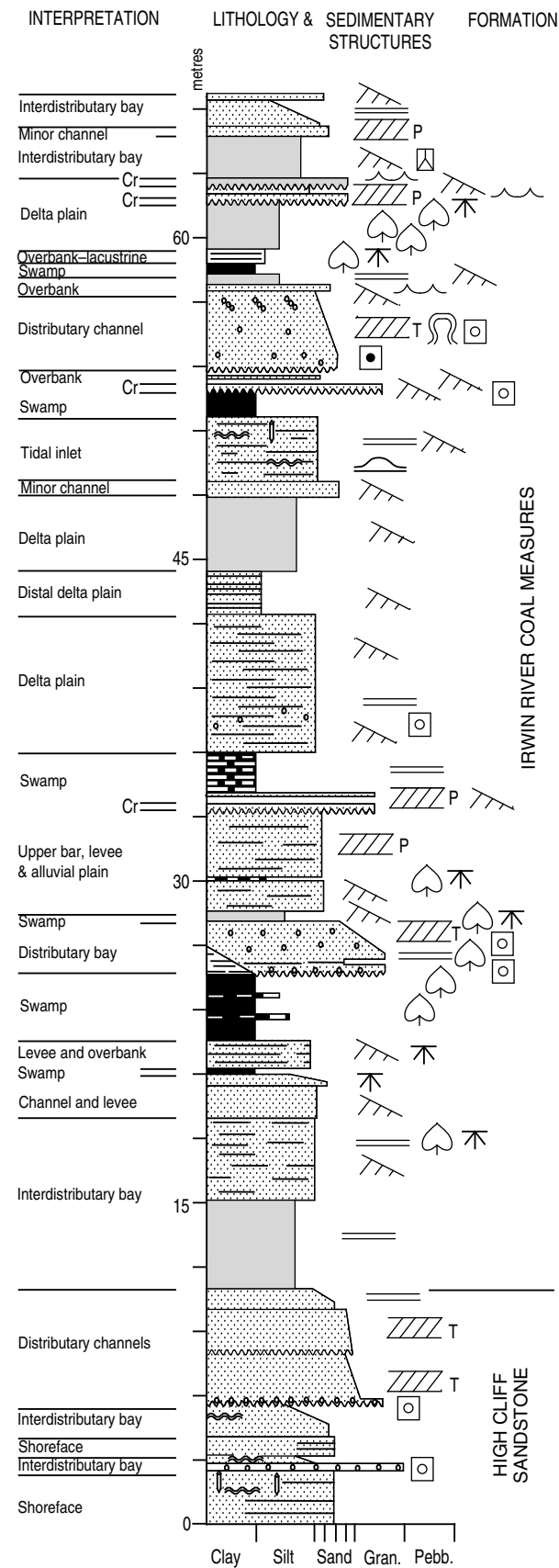


Figure 19. Measured section, North Branch, Irwin River (section extends from MGA 358450E 6797850N to 358810E 6798120N). See Figure 18 for reference (after McLoughlin in Haig et al., 1991)

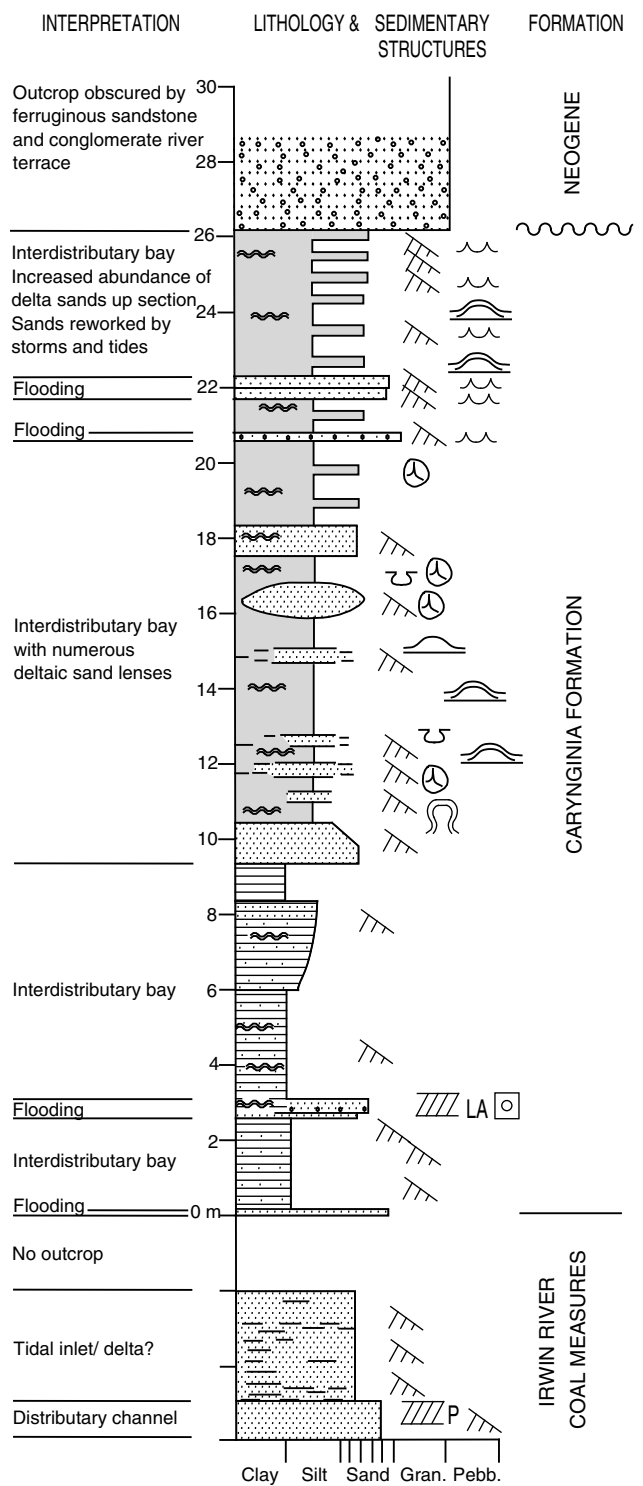


Figure 20. Measured section, South Branch, Irwin River (MGA 359290E 6795715N). See Figure 17 for reference (after McLoughlin in Haig et al., 1991)

conglomerate. Sandstone and conglomerate intervals typically contain internal cross-laminae, and have commonly been reworked by wave and storm action into symmetrical wave ripples and hummocky cross stratification. Erratic pebbles and boulders of granite and metamorphic rock are common within the unit and were probably transported by ice rafting (Fig. 22e). The facies are similar to those of the Holmwood Shale suggesting a comparable environment of deposition. Extensive bioturbation is common, with forms assignable to *Planolites*, *Rosselia*, *Teichichnus*, and *Phycodus*?, together with minor *Skolithos*.

The transitional lower part of the Carynginia Formation is well exposed in the South Branch of the Irwin River (Figs 20 and 22f). Much of the upper part of the formation in the Irwin River area is poorly exposed or concealed by Neogene duricrust or ferruginous river-terrace sandstones. The non-marine Wagina Sandstone disconformably overlies the formation.

The only macrofossils recorded from outcrop of the Carynginia Formation are 'Aviculopectens and *Anthracosia*-like shells and occasional fish' reported by David and Sussmilch (1931), possibly from the fossil locality shown in 'Carynginia Creek' by Clarke et al. (1951). Marine invertebrate faunas have rarely been reported in core from petroleum exploration wells, but none have been described. The siltstone-dominated lithology, evidence of wave reworking of sediments, dropstones, intense bioturbation, sporadic invertebrates, and abundant acritarchs (Segroves, 1971) indicate deposition within relatively low energy environments with restricted access to open-marine conditions, such as interdistributary bays. Segroves (1971) proposed an Artinskian–Kungurian age based on palynomorph assemblages (Backhouse, 1993).

Wagina Sandstone

The Wagina Sandstone (Clarke et al., 1951) is the only uppermost Permian formation that outcrops in the northern Perth Basin. The type section is in the South Branch of the Irwin River near Wagina Well, but as these exposures are poor, Playford and Willmott (in McWhae et al., 1958) proposed that 'the main reference section for the formation be located [25 km to the south] near Woolaga Creek commencing at Red Hill ... and continuing to the east'.

The Wagina Sandstone consists chiefly of fine- to medium-grained cross-bedded clayey sandstone with lesser amounts of conglomerate, siltstone, shale, and coal. The unit is up to 250 m thick, although the upper contact is not preserved in outcrop, and rests conformably or disconformably on the Carynginia Formation in the Irwin River district but in the subsurface to the west lies with a mild angular unconformity on Lower Permian strata. The unit is restricted to the northern portion of the Perth Basin having been either not deposited or removed by Late Permian or Mesozoic erosion from other areas (Playford et al., 1976). Fossil plants are scattered in these fluvial deposits. Palynological data indicate a Kungurian–Guadelupian age (Segroves, 1971; Kemp et al., 1977). In the Dongara area, coeval

shoreface sandstone and marine carbonate facies have been referred to as the Dongara Sandstone and Beekeeper Formation, respectively (Mory and Iasky, 1996). The upper Permian subsurface sections have also been referred to wholly, or in part, as the 'basal Triassic sandstone' and 'Yardarino Sandstone' (Hosemann, 1971; Playford et al., 1976).

Mesozoic

Mesozoic strata are confined to the west side of the Urella Fault. Outcrops mostly belong to the Upper Jurassic Yarragadee Formation or the uppermost Jurassic to earliest Cretaceous Parmelia Group, apart from a poor but fossiliferous exposure of the Cadda Formation on the west side of Enanty Hill (Coleman and Skwarko, 1967; Kendrick and Brimmell, 2000). The low maturities measured in the Irwin River Coal Measures east of the Urella Fault (about 0.5% vitrinite reflectance) imply the Permian strata were buried by about 500–1000 m of Mesozoic strata, whereas the Triassic to Cretaceous section west of the fault is up to 3500 m thick.

Locality 6: Coalseam Conservation Park

Summary: Good to excellent riverbank and cliff exposures along Irwin River showing Lower Permian marine and fluvial facies of the Holmwood Shale (includes type section of Fossil Cliff Member), High Cliff Sandstone (type section), Irwin River Coal Measures (type section), and Carynginia Formation.

Location: About 28 km north-northeast of Mingenew (Fig. 4); Fossil Cliff: MGA 357785E 6789390N; High Cliff: MGA 358580E 6797235N; North Branch: MGA 358450E 6797850N to MGA 358810E 6798120N; South Branch: MGA 358870E 6795830N to MGA 359290E 6795715N, MULLEWA 1:100 000 sheet.

Access: Coalseam Conservation Park (previously known as Coalseam Reserve) is a small national park, which is well signposted from Mingenew and Mullewa. Within the park High Cliff and Fossil Cliff (400 m upstream on opposite bank) are best accessed via the 'River Bend' area. The North Branch is upstream from 'Fossil picnic area' north of 'Irwin Lookout' (at the top of High Cliff), and the South Branch is next to the 'Miners Camp'. Several hours should be set aside to examine these exposures. Barbeques and toilets are available at 'River Bend' and 'Miners Camp', and there are also information panels at 'River Bend'. Camping is permitted at 'Miners Camp', and a ranger is in attendance during the winter months. The best time to visit this area is in winter or early spring because salt otherwise encrusts much of the sandstone facies along the river. The area is registered with the National Estate (Place ID: 9683).

Geology: Coalseam Conservation Park contains the best-exposed Lower Permian sections in the basin along the North and South Branches of the Irwin River where the upper part of the Holmwood Shale, High Cliff Sandstone, Irwin River Coal Measures, and Carynginia

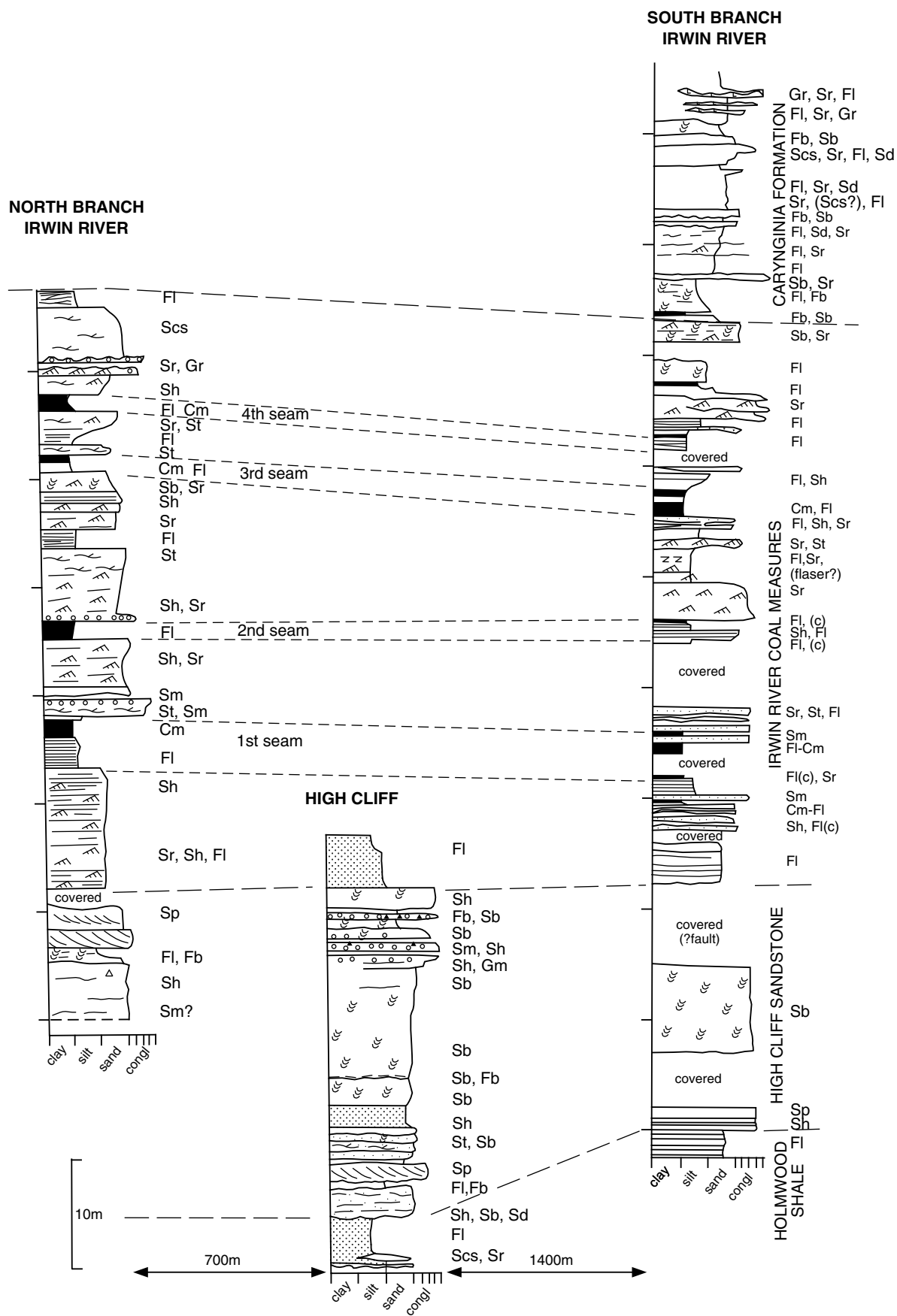


Figure 21. Correlation of Lower Permian sections at High Cliff, and North and South Branches, Irwin River (modified from Eyles et al., in prep.)

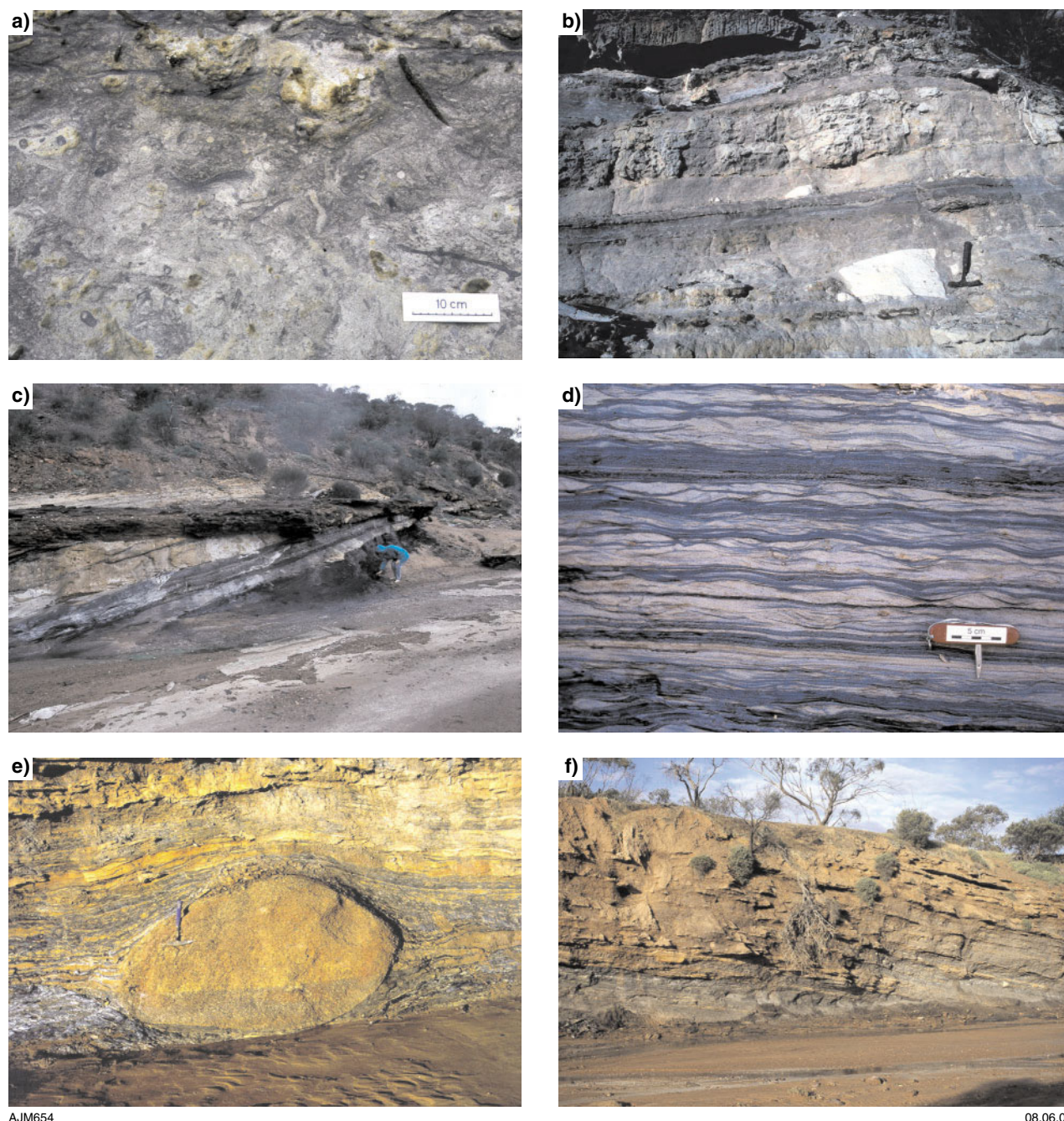


Figure 22. Lower Permian outcrops on the Irwin River: a) bioturbation in the High Cliff Sandstone (MGA 358580E 6797235N); b) granite dropstone, High Cliff Sandstone (MGA 358580E 6797235N); c) adit in coal, Irwin River Coal Measures, North Branch (MGA 358600E 6798100N); d) wave ripples, Irwin River Coal Measures, South Branch (MGA 358700E 6795830N); e) large dropstone, Carynginia Formation, South Branch (MGA 358950E 6795800N); f) lower Carynginia Formation, South Branch (MGA 358870E 6795830N)

Formation are exposed. These sections show a variety of sedimentary structures, and have been affected by minor normal faults with similar orientations and sense of movement to major faults in the region, as well as rare minor thrust faults.

Fossil Cliff, on the north side of the river, is the type section of the Fossil Cliff Member at the top of the

Holmwood Shale (Fig. 17). The member consists of grey, fossiliferous siltstone with thin to medium beds of fossiliferous limestone. The southeastwardly steepening of dips in Fossil Cliff may be the result of rotation along a normal fault (possibly controlling the river course) because there is a minor normal fault dipping steeply northwest on the opposite side of the river. Note that extensive jointing is parallel to this structure.



Figure 23. High Cliff showing the unconformable contact between the Lower Permian and Cenozoic units. Panorama compressed 50% horizontally

At High Cliff on the south side of the river, the contact between the grey siltstone of the Holmwood Shale, and white and red, feldspathic, cross-bedded and bioturbated sandstone of the High Cliff Sandstone, is clearly visible. The latter unit consists of a broadly upward-coarsening sequence of highly bioturbated silty sandstone (Figs 18 and 22a). The predominantly carbonaceous and highly bioturbated sandstone beds contain large angular to subangular granite, quartzite and chert erratics, up to 60 cm across (Fig. 22b). The contact with the overlying Irwin River Coal Measures is placed at the first appearance of carbonaceous siltstone about two-thirds of the way up the section. The oblique orientation of most of this exposure makes the discordance in bedding between the Permian section, which dips 10° east, and the flat lying Cenozoic section difficult to locate (Fig. 23).

Both northeast- and northwest-dipping normal faults are present in the Holmwood Shale west of High Cliff. Northeasterly dipping faults are syndepositional, because some minor structures are overlain by beds that show no displacement, consistent with northeast–southwest Permian extension as outlined by Byrne and Harris (1992) and Harris (1994).

The type section of the Irwin River Coal Measures is exposed on the south side of the river upstream from High Cliff and Fossil Cliff, and contains four low-rank coal seams interbedded with coarse- to fine-grained sandstone, siltstone, and claystone (Figs 19 and 22f). Minor southeasterly dipping normal and northeasterly dipping reverse faults are present.

Siltstone, mudstone, and thinly bedded sandstone of the overlying Carynginia Formation are well exposed in the South Branch of the Irwin River (Figs 20 and 22f). Bioturbation and abundant carbonaceous material indicate deposition in either a shallow-marine or lacustrine environment; however, trace fossils on the base of some sandstone beds are more suggestive of marine conditions. Scattered dropstones in the section (Fig. 22e) indicate glacial conditions continued into the Artinskian. Small-scale slumps suggest some slope instability during deposition, and rippled poorly sorted coarse-grained to pebbly sandstone beds and possible hummocky cross-bedding indicate this material was dumped from ice and further transported by wave activity. The contact with the underlying coal measures in this section is abrupt, and may be a third- or fourth-order sequence boundary. In the North Branch, the contact lies on the northern bank of the river, but it is often covered by sand. It is marked by an erosion surface with granules and some small pebbles at the base, and is immediately overlain by the typical Carynginia Formation shale–sand cycles.

Locality 7: Irwin River, west of Depot Hill

Summary: Cliff section showing fining-up cycle in fluvial facies of the Upper Jurassic Yarragadee Formation.

Location: About 11 km west-northwest of Mingenew (Fig. 4), MGA 338000E 6774250N, MINGENEW 1:100 000 sheet.

Access: Park 1.2 km west of the junction of Strawberry Northeast Road with Depot Hill Road, and walk about 300 m south through the bush. For safety, park on the abandoned road to the north (MGA 338030E 6774540N). The site is on a Shire of Mingenew reserve open to the public.

Geology: A 10 m-thick fining-up cycle in the Upper Jurassic Yarragadee Formation is exposed on the south bank of the river. The lower contact of this cycle near the east end of the outcrop is on contorted silty sandstone (Fig. 24a). Large cross-beds in coarse pebbly sandstone at the base of the cycle indicate a westward paleocurrent flow (Fig. 24b; Mory, 1995, fig. 10, locality 424). The cross-beds appear to become progressively smaller towards the thin white siltstone at the top of the section. The section is interpreted as a fluvial channel-fill sequence capped by bar-top deposits with flow progressively shallowing as the channel migrated laterally.

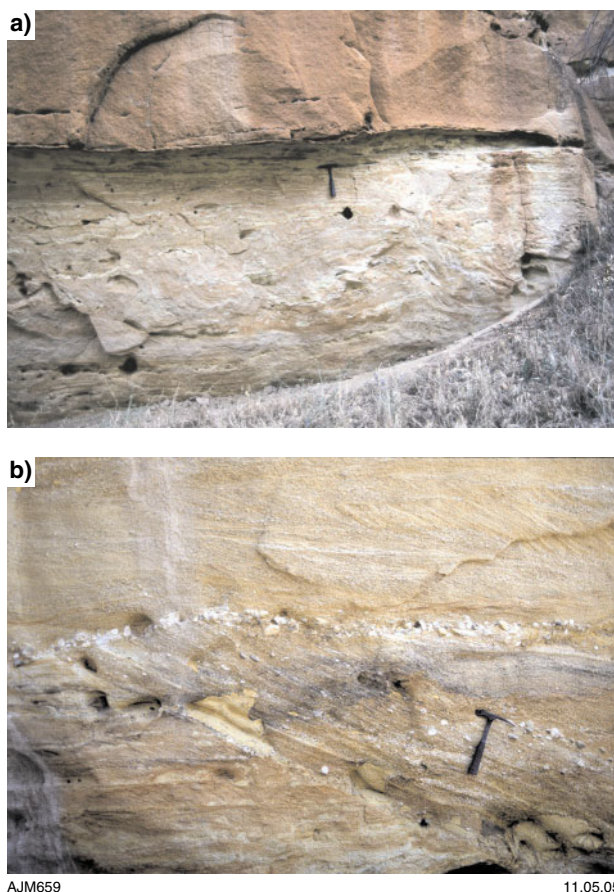


Figure 24. Fining-up cycle in Yarragadee Formation, Irwin River: a) lower contact with contorted beds; b) cross-bedding in lower part of cycle (MGA 338000E 6774250N)

Dongara area

Background geology

The Dongara area contains a moderately complete Lower Permian to Upper Jurassic succession in the subsurface (Mory and Iasky, 1996), and several gas- and oilfields (Owad-Jones and Ellis, 2000). In 2003–04, production from these fields was valued at \$123 million. Outcrop near Dongara is poor and limited to Cenozoic units and the Upper Jurassic Yarragadee Formation, with the only exception being outcrops of the mid-Jurassic Cattamarra Coal Measures and Cadda Formation at Mount Hill, 26 km northeast of Dongara. Cenozoic units cover much of the area and are dominated by Holocene deposits along the coast, and the Pleistocene Tamala Limestone that extends up to 20 km inland, and ferruginous duricrust of probable Miocene age east of the Gingin Scarp (Mory, 1995).

Locality 8: Leander Point, Port Denison

Summary: Low coastal cliffs with coral reef and eolian facies of the Pleistocene Tamala Limestone.

Location: About 3.5 km south-southwest of the Dongara post office (Fig. 4), from MGA 297450E 6759400N to MGA 297550E 6759280N, DONGARA.

Access: The low cliff is just south of the red and white obelisk (Fisherman's Memorial) next to the car park at the southern end of the Port Denison marina. To get to the thickest and most accessible sections, walk 150 m to the southwest along the top of the cliff. Alternatively, drive to the kiosk on the beach at the end of South Tops Drive off George Street, and walk 400 m northwest along the beach towards Leander Point. The locality is best viewed at low tide, taking care of the uneven and sharp limestone

surfaces; occasionally, the southwest end is obscured by washed up seaweed.

Geology: First noted by Hartmeyer (1907) and described by Teichert (1946), a Pleistocene reef is exposed in a low sea cliff up to 2.5 m above sea level (Fig. 25). The reef consists of bafflestone (Fig. 26a) of branching *Acropora* in a shelly calcarenite–calcirudite matrix, and of bindstone (Fig. 26b) of large palmate *Acropora* bound by coralline algae and shelly calcarenite–calcirudite. According to Fairbridge (1950) the reef contains 'reef-building corals (*Acropora*, *Platgyra*, *Favites*, etc.), and encrusting *Lithothamnion* layers. In parts of the reef the lithothamnoids make up 80% of the volume, but, in general, they form the upper part of the reef, corresponding to the former shallowest-water zone.' The shape of the wave-cut platform in front of the cliff suggests that this was a platform reef similar to those of the present-day Houtmann Abrolhos about 100 km to the west-northwest of Leander Point near the edge of the continental shelf.

Stirling et al. (1995) dated coral (mainly faviids) from the reef using the high precision U-series method. They obtained ages ranging from about 122 to 127 Ka, the same as they obtained for a similar reef at Rottnest Island. Johnson et al. (1995) dated corals from a similar *Acropora*-dominated reef at Cape Burney, about 40 km north of Leander Point, at 120 to 132 Ka using electron spin resonance. The Leander Point, Cape Burney, and Rottnest Island Pleistocene reefs are at about the same height above present sea-level implying sea level was at least 2 m above the present level.

Some of the southernmost coral–algal reefs on the Western Australian continental shelf with well-developed *Acropora*-dominated platform reefs are in the Houtmann Abrolhos islands at 28–29°S. During the last interglacial period *Acropora*-dominated reefs extended further south (at least to Rottnest Island at 32°S) implying the south-flowing Leeuwin Current brought warmer waters further south at that time. Hatcher (1991) examined the influence



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Figure 25. Sea cliff in Pleistocene coral reef, Leander Point (MGA 297550E 6759280N)



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Figure 26. Pleistocene coral facies, Leander Point (MGA 297550E 6759280N): a) bafflestone formed of branching *Acropora*; b) bindstone formed of palmate *Acropora*

of the Leeuwin Current on the distribution of coral reefs along the coast. He questioned whether sea temperature was the dominant influence on reef growth in the region: 'the Leeuwin Current's role in maintaining apparently low rates of nutrient delivery to the benthos, in combination with its elevation of sea temperature and advection of planktonic spores and larvae, serves to inhibit the development of marine macrophyte communities, which compete effectively with coral reef-building communities' (Hatcher, 1991). According to Hatcher (1991), the minimum mean monthly sea-surface temperature at the Houtmann Abrolhos is 19.8°C (with an absolute minimum of 17.6°C); at Dongara the minimum mean monthly sea-surface temperature is 18.5°C.

Locality 9: Lake Thetis, Cervantes

Summary: Holocene stromatolites and microbial mats on margin of small lake formed in an interdunal depression.

Location: About 1.2 km southeast of Cervantes post office, MGA 315500E 6623400N, WEDGE ISLAND.

Access: About 800 m south of the Department of Land Conservation office on the outskirts of Cervantes, or turn east from Hansen Bay Road, 300 m south of Cervantes Road. The best time to see the stromatolites is in late summer and autumn when the level of the lake is lowest. The site is signposted as a local tourist attraction.

Geology: Lake Thetis lies about 1.5 km inland from the present shoreline and formed in an interdunal depression in the Holocene Quindalup Dune System (Grey et al., 1990). It is a small lake that contains permanent water to a maximum water depth of 2.25 m, although the waterlevel shows seasonal variation. There is no substantial surface drainage into the lake, which is apparently fed by direct rainfall and ground water. According to Grey et al. (1990), there is no evidence for a subterranean connection to the sea. Stromatolites are forming in this metahaline lake through microcrystalline carbonate precipitation mainly within cyanobacterial *Entophysalis* biofilms. The developing stromatolitic structures are crudely laminated and some exhibit digitate columnar branching. Grey et al. (1990) considered the age of the interdunal depression containing Lake Thetis to be about 3–4 ka, based mainly on a bivalve assemblage in a coquina exposed in the quarry adjacent to the northern edge of the lake. Carbon-14 dating of bivalves from this locality indicates an age of 5600 ± 260 years BP (Mory, 1995a). The assemblage is similar to that in the middle Holocene strata of Rottnest Island (Playford, 1988).

Physical and chemical factors affecting the lake are listed in Table 1. As mapped by Grey et al. (1990), the substrate of the lake and adjacent foreshore is zoned in a concentric fashion based on different microbial mat types (Fig. 27a). Five types have been recognized (Table 2), and three of these may be visible from the shore. The crenulate mat can be seen in the seasonally flooded high foreshore areas where it grows in a reticulate pattern of ridges and blisters a few centimetres in diameter due to periods of desiccation. During February, at the height of summer, the mat will be desiccated and extremely friable.

Table 1. Physical and chemical factors at Lake Thetis (from Grey et al., 1990)

Mean rainfall	May to September	390 mm
	September to April	170 mm
Annual evaporation		1700 mm
Mean annual maximum temperature		24.6°C
Mean maximum temperature (February)		>30°C
Maximum temperature variation		<10°C to >37°C
Summer winds		southwesterly
Winter gales		northwesterly
Salinity		39–53 gL ⁻¹
Alkalinity (carbonate plus bicarbonate)		0.5% meq L ⁻¹
pH		8.28 – 8.6
Maximum water depth		2.25 m

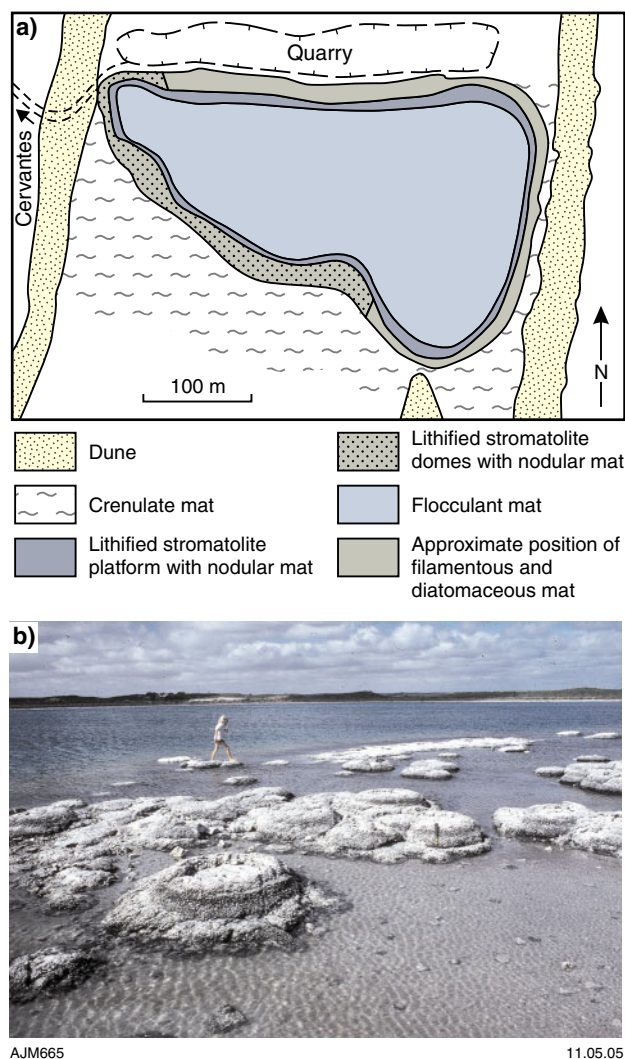


Figure 27. Lake Thetis: a) sketch map showing distribution of mat types (after Grey et al., 1990); b) Holocene stromatolites (MGA 315500E 6623400N)

Nodular mat is best seen in the splash zones around the edges of stromatolite domes along the southwestern shoreline (Fig. 27b) where it is formed of aggregations of nodules (0.5–10 cm diameter) on the lower surfaces of the stromatolites. Diatomaceous mat forms an orange-brown gelatinous band in the shallows, commonly just below or coating the nodular mat. The distribution of the diatom mat is probably tightly constrained by light penetration because it is nearly always about 25 cm below the surface and it migrates as lake levels change to maintain this position. The lithified surfaces of many of the stromatolites contain abundant diatom frustules.

The floor of the lake beneath the flocculant mat is composed of fine carbonate mud, with shell fragments, aragonite, and red-purple organic material composed mainly of purple sulfur bacteria (Grey et al., 1990). Silica is also being deposited inorganically as light brown organic particles containing traces of calcium, sulfur, and chlorine (MW Pryce, as cited by Grey et al., 1990). The purple mud of the lake floor includes irregular sandy

Table 2. Mat types in Lake Thetis (after Grey et al., 1990)

Mat Type	Location and substrate	Gross morphology and colour	Microbial community
Crenulate mat	above high waterlevel on coarse, calcareous sand; position varies seasonally	reticulate ridges and blisters on surface producing alternating layers of organic rich sand and mud; black to olive green	predominantly filamentous but with some coccoid cyanobacteria. Genera include <i>Calothrix</i> , <i>Scytonema</i> , <i>Gloeocapsa</i>
Nodular mat	littoral to mid-foreshore zone on lithified stromatolite domes and reef; changes with water line position	on SW shore mat forms nodules in clusters with an irregular surface and abundant mucilage; on N shore mat is patchier with less surface relief; produces indistinct laminations; black to grey	coccoid cyanobacteria; including <i>Gloeocapsa</i>
Filamentous mat	low marginal shelf that is permanently submerged; on lithified plates and angular fragments - in cracks, on underside of plates and as a fragile benthic mat over flocculent mat with very little seasonal change	film and/or fragile coating; produces no laminations; bright green	filamentous cyanobacteria; including <i>Oscillatoria</i>
Diatomaceous mat	marginal shelf, at water depths below 1.5 – 2 m, on lithified stromatolites and plates; changes position with change in water depth in lake	mucilaginous coating; produces no laminations; beige–brown	diatoms
Flocculent mat	permanently submerged in centre of lake; surface approximates oxic/anoxic interface; sometimes is dispersed throughout water column and concentrated at water's edge	gently undulating mat up to about 50 cm thick, with distinct sediment–water interface where surface undisturbed; produces no laminations; purple–pink with blue–green patches on surface	filamentous and coccoid cyanobacteria, diatoms, purple sulfur bacteria; genera include <i>Oscillatoria</i> , <i>?Synechocystis</i> , <i>?Thiocystis</i> / <i>Thiocapsa</i>

laminae, and fine sand-sized irregular carbonate micro-nodules (Grey et al., 1990).

The margins of the lake have terraces of lithified carbonates and associated unconsolidated sediment. Grey et al. (1990) recognized three terraces of coalesced, planed and domal stromatolites. Fractured and weathered domes reveal that the centres of many of the stromatolites show a pattern of crude concentric upwardly convex laminae, and most include internal morphological variation. In some, there is a thrombolitic core (without layers) with an outer layer (up to 15 cm thick) of digitate branching columns. Grey et al. (1990) noted that branching seems to be confined to areas of low wave activity. Fenestrae (about 1 mm high and 10 mm or more in length) and larger elongate cavities may develop between the laminae.

Grey et al. (1990) noted that the lithified carbonate platform extends up to 10 m into the lake where there is an abrupt slope to the unconsolidated floor of the central part of the lake (at 2–2.5 m water depth). The surface of the platform consists of a crust (1–5 cm thick) including a massive white papillate to botryoidal surface layer (0.1–1.0 cm) and a fenestral cream lower layer (0.5–4.0 cm) with the basal section commonly coloured green due to associated micro-organisms.

Reitner et al. (1996) and Arp et al. (2001) discussed the method of calcification of the Lake Thetis stromatolites.

According to Reitner et al. (1996):

‘The recent growth results mainly from calcifying *Entophysalis* films which are forming a more or less laminated crust. Within the deeper parts of the *Entophysalis*-biofilm the outer basophilic polysaccharide envelopes contain abundant heterotrophic bacteria. Calcification events exactly start at these points. The older, subfossil portions of the microbialites are characterized by plumosely arranged *Scytonema*-filaments which are enclosed by fibrous aragonite. Within small cryptic primary and secondary cavities clearly laminated organomicrites are lining cavity walls. The formation of this type of ‘microstromatolites’ is related to organic films, which contain no active microbes. These organic films are composed of degraded organic material (polysaccharides, proteins etc.) acting as matrices and templates for nucleation and growth of organomicrites and fibrous aragonite crystals’.

Locality 10: Pinnacles, Nambung National Park

Summary: Limestone pinnacles and rootlets in Pleistocene Tamala Limestone formed by reprecipitation of calcium carbonate around tree taproots.

Location: About 15 km south-southwest of Cervantes, MGA 324000E 6613000N, WEDGE ISLAND.

Access: Follow Pinnacles Drive south of Cervantes. Note that there is an entry charge to the park, but that it is accessible by two-wheel drive vehicles. Barbecues, information panels, tables and toilet facilities are provided, but camping is not permitted. The site is registered with the National Estate (Place ID: 10201).

Geology: The Pinnacles developed from deep differential weathering on the surface of the Tamala Limestone (McNamara, 1986). Weathering apparently took place preferentially along fissures in the limestone and residual columns of rock became covered by a residue of unconsolidated quartz sand. In the Pinnacles desert, much of the residual sand has been blown clear of the limestone columns by persistent winds (Fig. 28a) commonly exposing abundant calcified fossil rhizoliths (plant roots; Fig. 28b). Some residual sands with fossil soil horizons are present nearby (Fig. 28c). The following model for the development of pinnacles is from McNamara (1986):

1. Large taproots penetrated the eolian dune deposits while they were stabilized by vegetation and lithification. Dissolution and reprecipitation of calcium carbonate around the taproots alternated between wet winters and dry summers, thereby preferentially lithifying these areas.
2. A subsoil calcrete developed at the base of the thin humic layer on the surface of the dunes.
3. Cracking of the subsoil calcrete allowed preferential leaching of the underlying friable limestone by surface waters. After prolonged weathering only limestone pinnacles (originally lithified around tap roots) remain surrounded by residual quartz sand from the dune deposit.

Aboriginal artefacts (including flakes of chert) have been found in blowout depressions around the pinnacles and, in one instance, cemented to a pinnacle. Foraminifera in the chert indicate that the flakes are from an Eocene unit believed to lie on the now submerged continental shelf (Glover, 1975; Quilty, 1978). No exposures of this Eocene facies are known onshore in the Perth Basin.

Active coastal dunes of the Quindalup Dune System border the beach along the road into the Pinnacles. A 31.7 × 23 cm egg of the large, flightless, now extinct, Madagascan Elephant Bird (*Aepyornis maximus*) was found in 1992 buried in one of these Holocene dunes, and was dated at about 2000 years BP (Long et al., 1998). It is thought that the egg drifted on ocean currents from Madagascar rather than being transported by human intervention. In a discussion of alien vegetation, Rippey

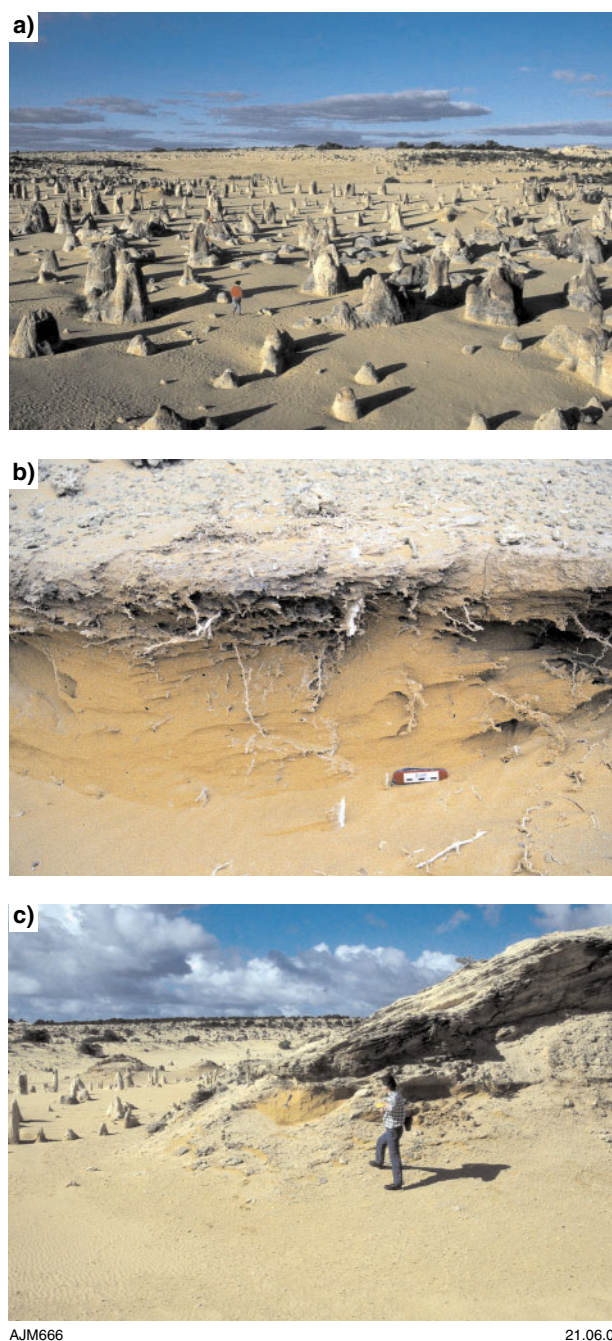


Figure 28. Tamala Limestone, Pinnacles Desert (MGA 324000E 6613000N): a) general view of pinnacles; b) fossil rhizoliths; c) silica and carbonate sand separated by a fossil soil horizon

and Rowland (1995) mentioned a South African study in which drift cards took about 18 months to float across the Indian Ocean from South Africa to Western Australia.

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