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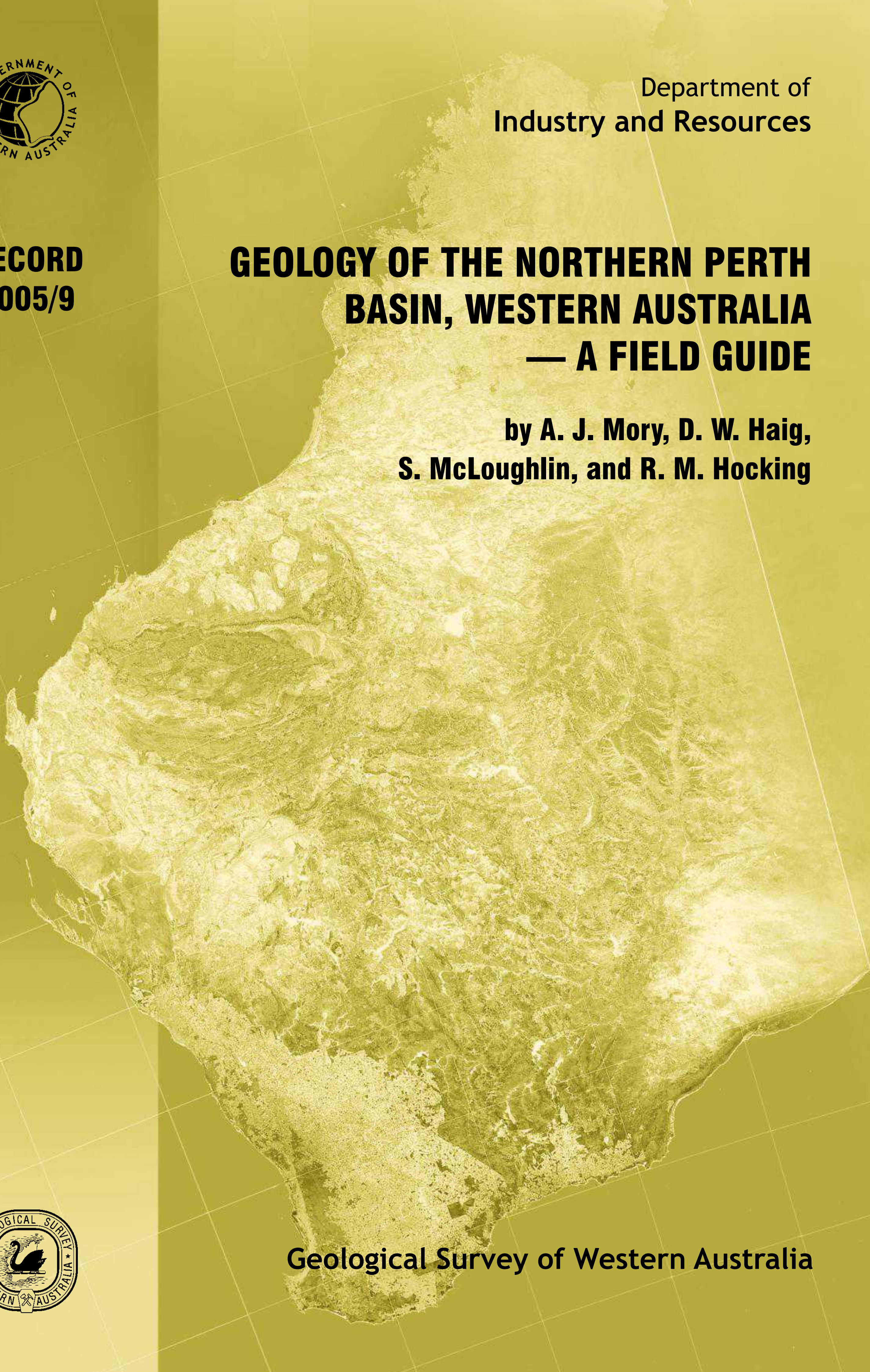

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 2005/9

GEOLOGY OF THE NORTHERN PERTH BASIN, WESTERN AUSTRALIA — A FIELD GUIDE

by
A. J. Mory, D. W. Haig[1], S. McLoughlin[2], and R. M. Hocking

[1] School of Earth and Geographical Sciences, The University of Western Australia
[2] School of Natural Resource Sciences, Queensland University of Technology

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Geology of the northern Perth Basin, Western Australia — a field guide

by

A. J. Mory, D. W. Haig[1], S. McLoughlin[2], and R. M. Hocking

Abstract

The northern Perth Basin lies between about 27° and 31°30'S adjacent to the Yilgarn Craton on the western margin of Western Australia. The basin contains up to 12 km of Ordovician and mid-Carboniferous to Cretaceous, primarily non-marine to shallow-marine strata below extensive thin, mostly non-marine, Cenozoic cover. This guide describes 37 localities in the basin, from Kalbarri to Gingin, including access and land tenure, and emphasizes stratigraphy, sedimentology, and palaeontology. These localities constitute the key exposures of the pre-Cenozoic succession in the basin and include most of the type sections defined in outcrop.

KEYWORDS: Ordovician, Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Pleistocene, Holocene, stratigraphy, sedimentology, palaeontology, Perth Basin.

Introduction

The Perth Basin (Fig. 1) is a north-northwesterly orientated rift basin on the western margin of Western Australia, adjacent to the Yilgarn Craton. The basin contains up to 12 km of Ordovician and mid-Carboniferous to Cretaceous, primarily non-marine to shallow-marine strata (Fig. 2), below extensive thin, mostly non-marine, Cenozoic cover.

Although of variable quality, the pre-Cenozoic outcrops in the northern Perth Basin (the portion north of about 31°30'N) provided the first insights to likely subsurface sections, with the first comprehensive outcrop study (Campbell, 1910) pre-dating the first subsurface study (for petroleum exploration, based on water bores) by Fairbridge (1949) by about 40 years. Previous subsurface studies were almost entirely directed to the sinking of shafts and adits, and the drilling of shallow bores in attempts to find coal near the Irwin River (Johnson et al., 1954). Consequently, much of the stratigraphy of the basin is defined from outcrop of limited lateral extent or isolated from other exposures, rather than in more complete subsurface sections in petroleum exploration wells. A summary of the type sections for the northern Perth Basin succession is provided in Appendix 1.

This guide is derived mostly from recent studies of the region by the Geological Survey of Western Australia (GSWA) and the University of Western Australia (UWA), and covers outcrops ranging in age from Ordovician to Holocene. The section on the Ordovician at Kalbarri has been modified from Hocking (2000). Information on most Cretaceous sections, and some other localities, has been adapted from unpublished field guides for the 1991 International Symposium on Ostracoda (Haig et al., 1991) and the 2002 International Symposium on Foraminifera (Haig, 2002). Lemmon et al. (1979) and Carter (1987) discuss the significance of many of the sites: some are listed as geological heritage sites on the Register of the National Estate (www.ahc.gov.au). Note that the emphasis on some localities is markedly different, especially for the abundantly fossiliferous Cretaceous exposures as opposed to the largely sedimentological emphasis for many of the other outcrops described.

Access

The northern Perth Basin has a good network of roads between the towns, as well as numerous farm tracks, so that few of the localities in this guide (Fig. 3) are far from

[1] School of Earth and Geographical Sciences, The University of Western Australia.

[2] School of Natural Resource Sciences, Queensland University of Technology.

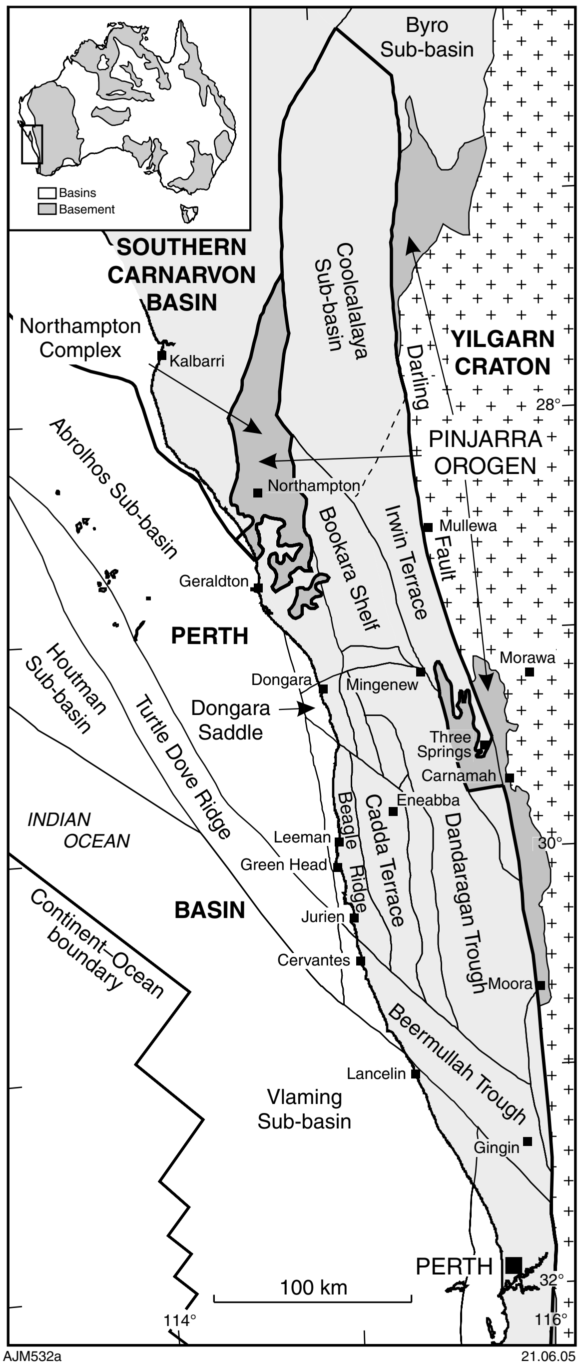

Figure 1. Regional structural setting, northern Perth Basin

vehicular access, although in some cases four-wheel drive is required. Some localities are in National Parks where an entry fee may apply, and in which sampling requires a permit from the Department of Conservation and Land Management*. If you intend to visit localities on private land, allow enough time to contact owners or managers before visiting as they are within their rights to ask individuals to leave, although this is rare. Specific details about how to contact the owner or manager are given under **Access** for each locality, and the tenure of private land is provided in Appendix 2. In addition to outcrops, it may be possible to visit operating mines or petroleum development facilities in the area if the operators are given sufficient notice (Table 1).

Gates and fences should be left as they are found, and crops or recently tilled ground should not be driven over. Some areas are particularly susceptible to fire in summer, so you may be asked not to smoke and to show that you have a fire extinguisher for your vehicle before crossing paddocks. Where sites are not easily accessible by two-wheel drive vehicles, the need for four-wheel drive or walking is specifically mentioned under **Access**. Particular care should be taken when driving on farm tracks and around the edges of paddocks, especially when the ground is wet. Two-wheel drive vehicles may have insufficient clearance to drive over soft harrowed or ploughed ground. Appendix 3 discusses various risks involved with examining outcrops, with brief suggestions on their management.

Accommodation

The northern Perth Basin is a popular tourist destination because of the rugged scenery around Kalbarri and wildflowers in mid-winter to early spring, so it is advisable to book accommodation beforehand, especially during school holidays. Towns along the coast have a wide range of accommodation available, but the choice is limited inland, especially in Mingenew and Mullewa. Farm stays throughout the region may be available.

Climate

The climate is typically Mediterranean with warm to hot, dry summers and cool, wet winters (Table 2). The best time to visit exposures along many rivers and creeks south of the Murchison River is in winter or early spring, as salt otherwise encrusts much of the sandstone facies. Also note that outcrops can change during winter or after summer cyclonic rain, especially those along active watercourses, often for the worse. For example, low exposures of the Irwin River Coal Measures in the bed of the North Branch of the Irwin River were buried by sand following heavy cyclonic rains in 1974, and low exposures in the South Branch are being buried gradually because of increased runoff in winter.

Regional geology

The Perth Basin is a north–south elongate rift or trough that covers about 100 000 km^2 along the western coast of Australia between latitudes 27°S and 34°30'S, and lies between the Archean Yilgarn Craton to the east and the edge of the continental shelf to the west (Fig. 1). The Pinjarra Orogen underlies the basin, and outcrops as fault-bounded, mid-basin ridges in the Leeuwin and Northampton Complexes.

* Ph. 08 9334 0333; www.calm.wa.gov.au

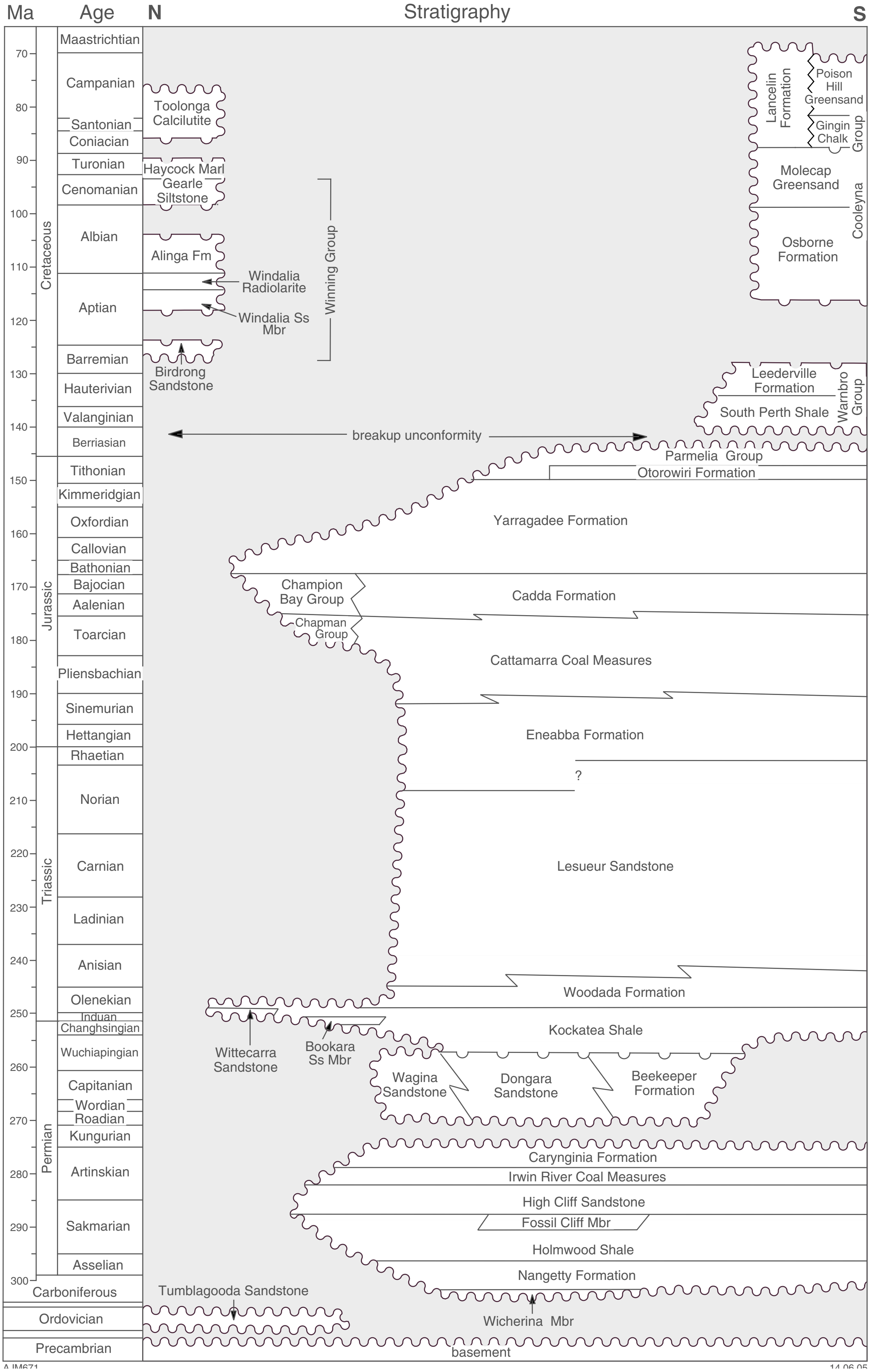

Figure 2. Pre-Cenozoic stratigraphy, northern Perth Basin. Timescale from Gradstein et al. (2004)

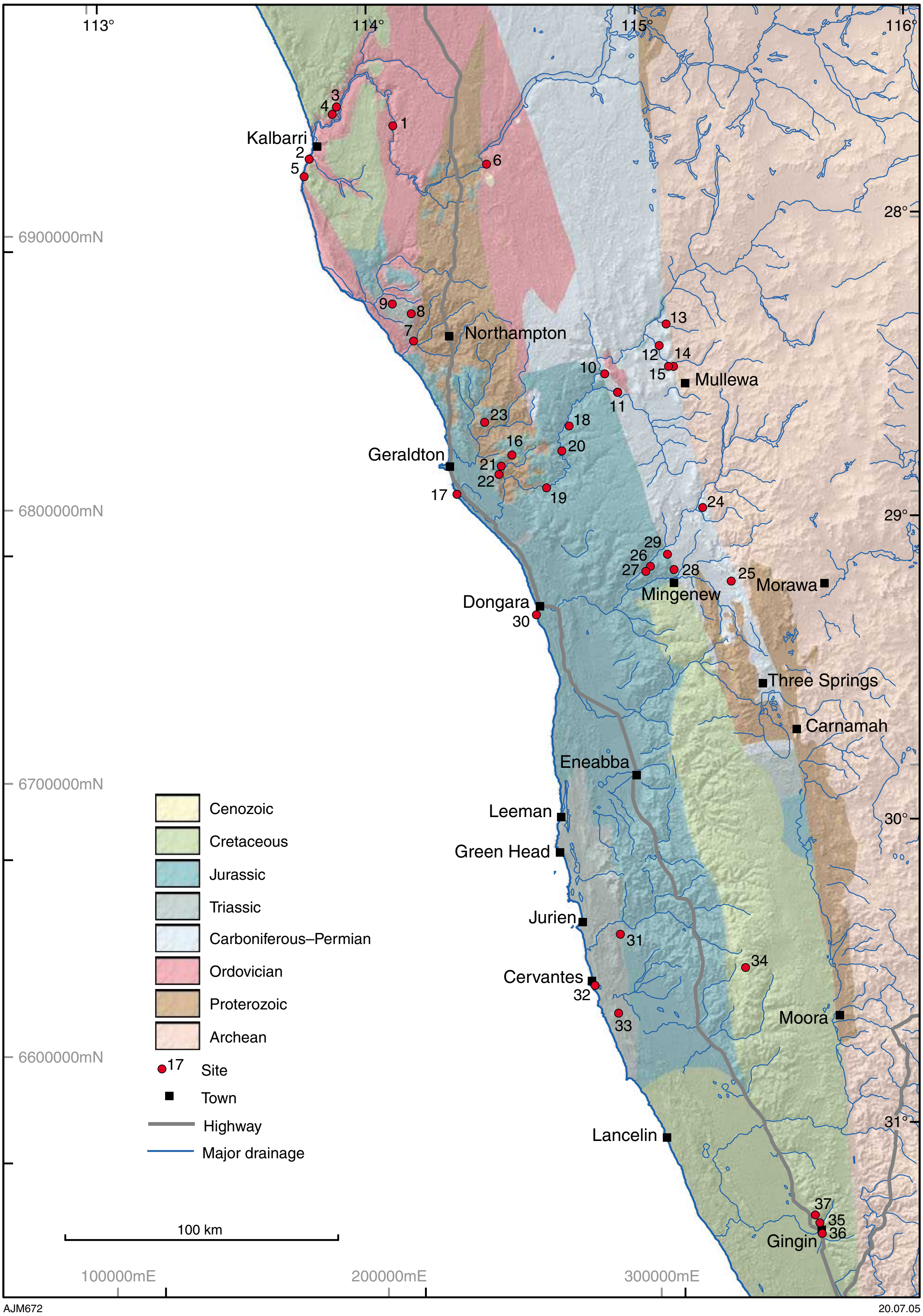

Figure 3. **Distribution of localities described in text, northern Perth Basin, superimposed over digital elevation image from NASA SRTM data compiled by M. Sandiford (http://jaeger.earthsci.unimelb.edu.au/Images/Landform/landform.html)**

Table 1. Contact details for operating mines and petroleum facilities, northern Perth Basin

Facility	*Operator*	*Address*	*Phone*
Petroleum			
Beharra Springs gasfield	Origin Energy	P.O. Box 373, West Perth, W.A. 6872	08 9324 6111
Dongara gas- and oilfield	Arc Energy	P.O. Box 574, West Perth, W.A. 6872	08 9486 7333
Hovea–Jingemia oilfield	Arc Energy	P.O. Box 574, West Perth, W.A. 6872	08 9486 7333
Mount Horner oilfield	Arc Energy	P.O. Box 574, West Perth, W.A. 6872	08 9486 7333
Woodada gasfield	Hardman Oil and Gas	P.O. Box 869, West Perth, W.A. 6872	08 9321 6881
Heavy mineral sands			
Cataby Heavy Mineral Sands	Tiwest	Brand Hwy, Cataby, W.A. 6507	08 9690 9200
Eneabba Heavy Mineral Sands	Iluka Resources	Brand Hwy, Eneabba, W.A. 6518	08 9956 9555 or contact the community relations officer on (08) 9360 4396
Port Gregory Garnet Mine	Garnet International Resources	George Grey Drive, Lynton, W.A. 6535	08 9923 6000
Other			
Dooka gypsum deposit (Dongara)	Manna Enterprises	10 Kearns Crs., Ardross, W.A. 6153	08 9316 8020
Gravity Discovery Centre		Military Road, Gingin WA 6503 P.O. Box 313, Gingin, W.A. 6503	08 9575 7577 www.gdc.asn.au

NOTES: Contact the production manager unless otherwise specified
Iluka Resources also has a heavy mineral sands deposit under development at Gingin with a planned life of 3.5 years

The northern part of the basin contains mainly clastic rocks of mid-Carboniferous – Early Cretaceous age (Fig. 2), 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). Ordovician redbed facies, typically associated with the Southern Carnarvon Basin, extend as far south as 28°45'S in the northernmost part of the Perth Basin, and are probably associated with an earlier northward-opening rift phase. Transgressive marine deposits characterize the late Early Cretaceous and Cenozoic, post-breakup phase of deposition in west Australia. In the onshore Perth Basin these are virtually undeformed.

Structural subdivisions of the northern Perth Basin (Fig. 4) mostly reflect the present structural configuration, which is dominated by Early Cretaceous deformation during the breakup of Gondwana. Isopach maps show that the large half graben of the Dandaragan Trough and the ridge along the present coast (Beagle Ridge – Dongara Saddle – Greenough Shelf) originated in the Early Permian. Similarly, the Urella Fault, which bounds the Irwin Terrace to the east of the Dandaragan Trough, probably had significant vertical movements in the mid-Triassic, as implied by the considerably lower maturity of the Permian succession to the east compared to the west. Most other subdivisions are based largely on subsurface data, and reflect the large block faults active at breakup. Earlier tectonism appears to have produced much smaller-scale structures, such as mid-Jurassic faults, which are evident only where seismic data quality is good. Few of the structural divisions can be delineated entirely from outcrop, and major faults are rarely exposed. The rotated fault blocks and anticlines are associated with gas- and

Table 2. Climate averages for towns in the northern Perth Basin

Town	*Mean daily temperature range (°C)*		*Mean annual rainfall (mm)*	*Mean annual evaporation (mm)*
	January–February	*July–August*		
Cervantes	17–31	9–20	570	2 100
Geraldton	18–33	9–20	460	2 400
Gingin	16–33	6–19	735	1 400
Kalbarri	19–34	10–22	396	2 400
Mingenew	19–36	7–19	441	2 500
Moora	18–34	7–17	460	2 000
Mullewa	19–37	7–19	340	2 500

SOURCE: Bureau of Meteorology, Perth

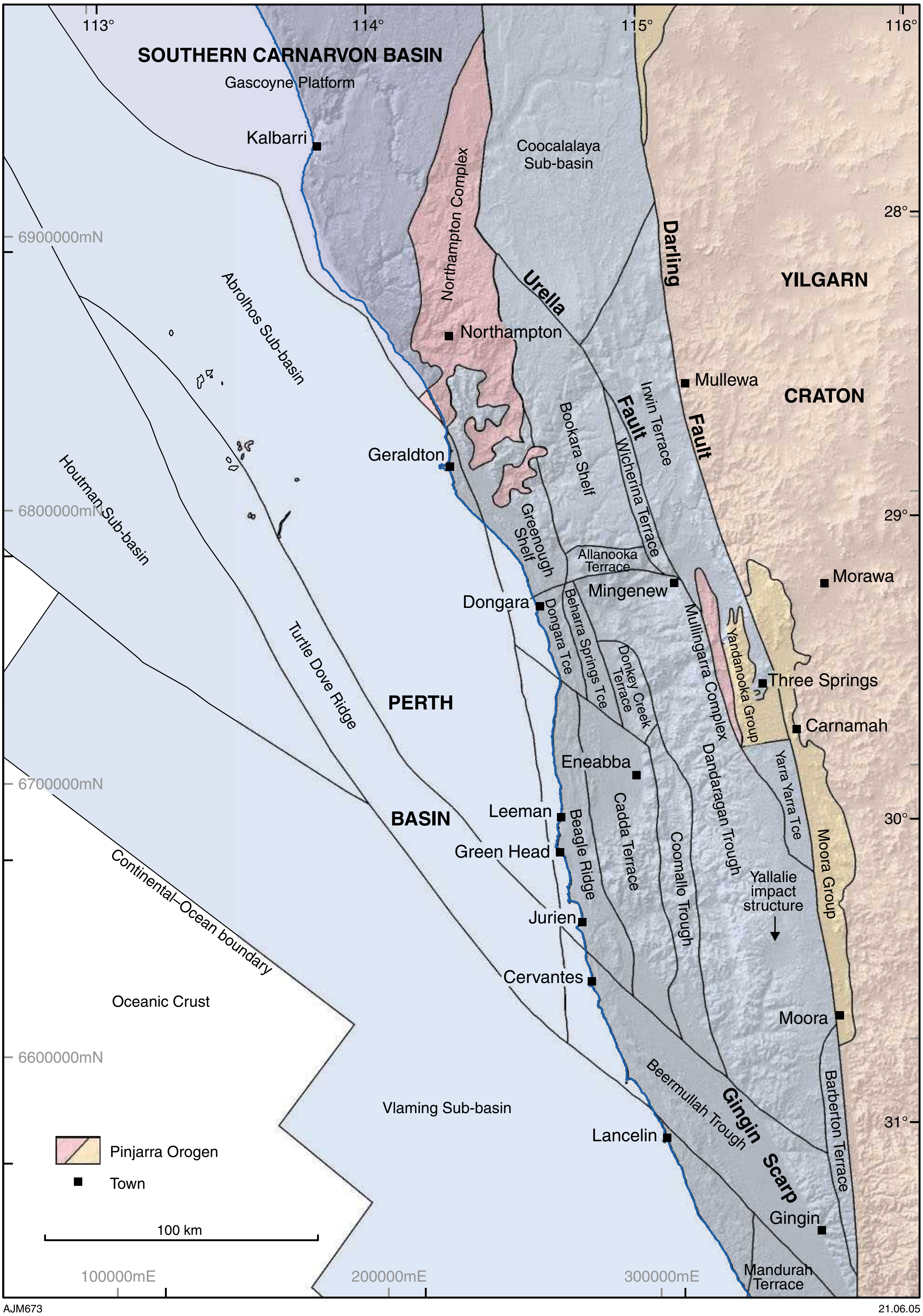

Figure 4. Tectonic divisions, northern Perth Basin, superimposed over digital elevation image from NASA SRTM data compiled by M. Sandiford (http://jaeger.earthsci.unimelb.edu.au/Images/Landform/landform.html)

oilfields described by Owad-Jones and Ellis (2000) and Buswell et al. (2004).

Cenozoic deposits cover most of the region, most of which are sand or ferruginous duricrust. The sand is derived from weathering of underlying units in situ (Newsome, 2000; Tapsell et al., 2003), rather than long-range eolian transport as proposed by various authors from the 1970s to the mid-1990s. These sediments are poorly dated but contain significant heavy mineral sand deposits preserved mostly in strandlines along the Gingin Scarp (Baxter, 1974). Duricrust of probable Miocene age covers much of the elevated parts of the region, and Pleistocene eolian carbonate sands extend up to 20 km inland from the coast.

Kalbarri area

Background geology

The area around Kalbarri is transitional between the Perth and Southern Carnarvon Basins. Triassic rocks 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. Some formations near Kalbarri are contiguous with the Perth Basin and these exposures are included in this guide because of their quality and proximity to the northern Perth Basin. The following locality descriptions are modified from the field guide to the Southern Carnarvon Basin (Hocking, 2000). For more detail on the Ordovician Tumblagooda Sandstone see Hocking (1991).

Ordovician

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., 2003). By comparison, Ordovician redbed deposition (Tumblagooda Sandstone) in braided fluvial, tidal sandflat, and coastal redbed settings covered the full extent of the Gascoyne Platform, at least 700 km from south of Kalbarri to Onslow in the north, and extends into the northern Perth Basin as far south as 28°45' (10 km east of Bringo). The Ordovician basin was a north–south-oriented, north opening, interior-fracture basin, which developed in equatorial to low tropical latitudes. The location and nature of the western margin of the Ordovician basin is unknown.

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 redbed facies are exposed in a section within which dips rarely exceed 5°. None of the other lower Paleozoic formations of the Southern Carnarvon Basin are exposed. North of the Murchison River the Tumblagooda Sandstone is overlain by Silurian shallow-marine dolomite, limestone, and evaporites in the subsurface. 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; however, 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 (Iasky and Mory, 1999, table 1), of which the most constrained was the Early Ordovician age based on palaeomagnetism (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 sharp-based megacycles of fluvially dominated facies overlain by tidal sandflat deposits or interdistributary bay deposits (FA1 to FA2, and FA3 to FA4). Fluvial palaeocurrents flowed to the northwest, with remarkably little scatter. The section at the Z Bend 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, northwestwards palaeocurrents. It was deposited as large, sheet-braided fluvial lobes, and grades upward 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 upward. 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-upwards 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.

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 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.

A fifth association (FA5), deposited as a conglomeratic alluvial fan or proximal braid-plain sequence, lies up-palaeoslope to the east of the Northampton Complex (Fig. 4). Stratigraphic correlation between FA5 and the remainder of the Tumblagooda Sandstone is not possible.

Triassic

In the Kalbarri region, Lower Triassic strata are exposed only in the coastal cliff section at Shell House, south of the town. 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 best exposed north of the Murchison River on Murchison House Station, at Meanarra Hill, and in the coastal cliffs (Table 3). 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 (Clarke and Teichert, 1948; Hocking et al., 1987; Lynch, 1991). 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) claims 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 3249090E 6938590N, GANTHEAUME*.

Access: Drive 12 km 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 short climb 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. 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

* Capitalized names refer to standard 1:100 000 map sheets.

Table 3. Cretaceous stratigraphy, Murchison House Station

Age	*Formation*	*Member*	*Thickness (m)*	*Main features*	*Environment of deposition*
Campanian	Toolonga Calcilutite	unit 3	up to 10	friable greenish marly calcilutite with thin indurated horizons; thin basal layer of small phosphatic nodules, and thin laterally extensive layer of flint nodules 7 m above base of unit	outer neritic
Santonian	Toolonga Calcilutite	unit 2	8	friable white chalk, intensely bioturbated, thin layers of small phosphatic nodules as well as layers of digitate or tabulate chert nodules; *Inoceramus* fragments common and commonly make up >50% of sand fractions	outer neritic
?Santonian	Toolonga Calcilutite	unit 1	0.5	friable glauconitic chalk with basal layer of nodules; overlies Alinga Formation west of woolshed, and unit 3 of Haycock Marl to the east	outer neritic
Turonian	Haycock Marl	unit 3	0.1	friable pink and white bioturbated marl with *Chondrites* burrows filled with chalk from overlying unit	outer neritic
Turonian	Haycock Marl	unit 2	1	friable pink bioturbated marl with *Chondrites*; a few narrow *Planolites* burrows	outer neritic
Turonian	Haycock Marl	unit 1	0.3	friable pink bioturbated marl with *Chondrites* burrows; laminations of glauconitic sand and fish debris thicker near base of unit; sharp basal contact	outer neritic
Cenomanian	upper Gearle Siltstone	–	up to 1	discontinuous lenses of friable, dark grey silty mudstone with a thin fine-grained glauconitic sandstone (about 10 cm thick) at top	mid-neritic
late early – middle Albian	Alinga Formation	–	up to 8	friable muddy glauconitic siltstone and fine- to medium-grained greensand; *Planolites*, *Chrondrites*, and *Zoophycus* dominate ichnofacies; belemnite guards locally abundant; overlies ?Windalia Sandstone Member at Alinga Point type section	mid-neritic
late Aptian – earliest Albian	Windalia Radiolarite	–	about 16	alternating friable and moderately indurated radiolarite-rich mudstone and siltstone, and indurated radiolarite beds; *Helminthopis* and *Zoophycus* ichnofacies; belemnite moulds in mudstone beds	inner neritic
–	?Muderong Shale	?Windalia Sandstone Member	up to 15	friable glauconitic sandstone with poorly preserved large ammonites	innermost neritic
?Barremian – early Aptian	Birdrong Sandstone	–	up to 16	friable, poorly sorted, medium- to coarse-grained quartz sandstone	shallow marine, shoreface to foreshore

a)

b)

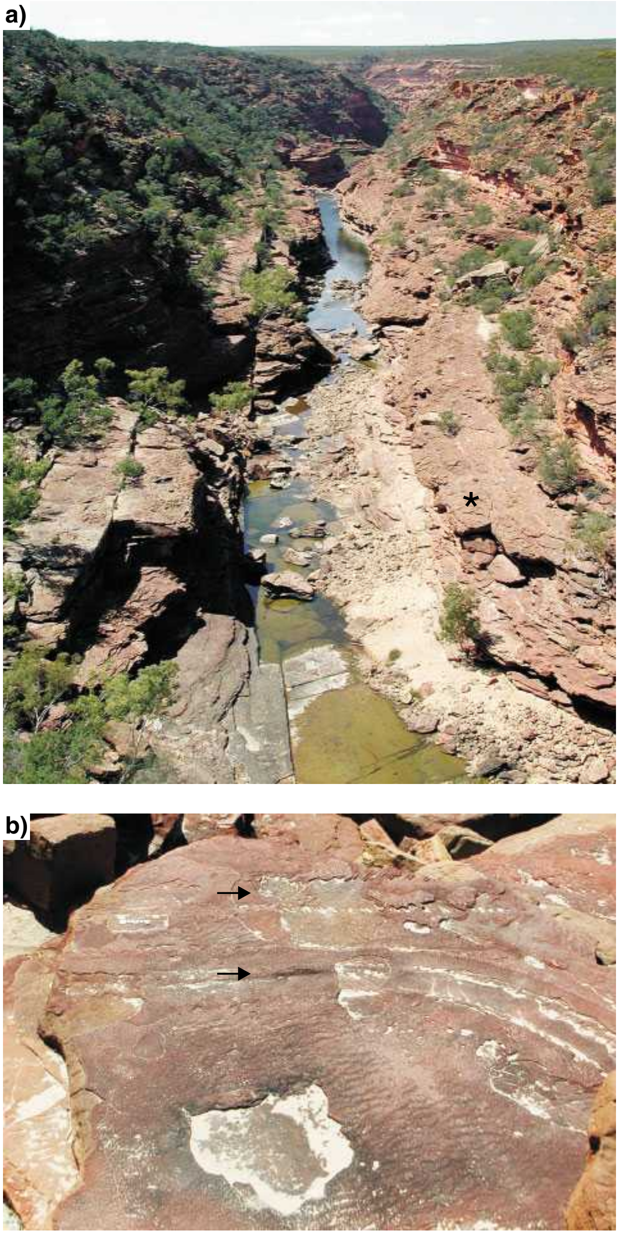

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Figure 5. Tumblagooda Sandstone, Z Bend showing: a) the joint control of the Murchison River. The asterisk marks the position of the channel shown in Figure 6. Photograph taken from MGA 249090E 6938590; b) arthropod trackways (arrowed) at the base of the Z Bend section (MGA 249075E 6938435N)

consists of a projecting bluff of mostly thin-bedded, tidal 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. 5a). 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.

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, are two large arcing sets of eurypterid tracks, superimposed on wave ripples (Fig. 5b). Several sets of wave ripples, some wind adhesion surfaces and setulfs, can be seen between the track ways 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. Palaeocurrents 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 palaeocurrent directions are reversed, implying reworking by marine currents.

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. 6). 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.

Within the fluvial intercalation, there is a large, easterly facing overhang below the lookout that commonly has several seeps dripping 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.

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

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Figure 6. Large channel within the Tumblagooda Sandstone, Z Bend, Murchison River (MGA 249290E 6938640N)

Locality 2: Red Bluff

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

Location: Four kilometres south of Kalbarri, MGA 218055E 6927810N, GANTHEAUME.

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 mid- 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. Palaeocurrents were unimodal to the northwest, and very tightly clustered. Vertical burrows within the sandstone, visible in some overhangs between the car park and the face of Red Bluff (Fig. 7), 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. The ichnofauna is described in Trewin and McNamara (1995). 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. It is a distinctive pebbly sandstone to pebble conglomerate bed about 1 m thick, which extends along the coastal gorges in the south about 40 km north, and can be used as a stratigraphic marker.

Near the top of the terraces, the fluvial FA3 facies grade 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. 8). Where bioturbated, sediments were deposited below high-tide level, and where non-bioturbated, above high tide and exposed.

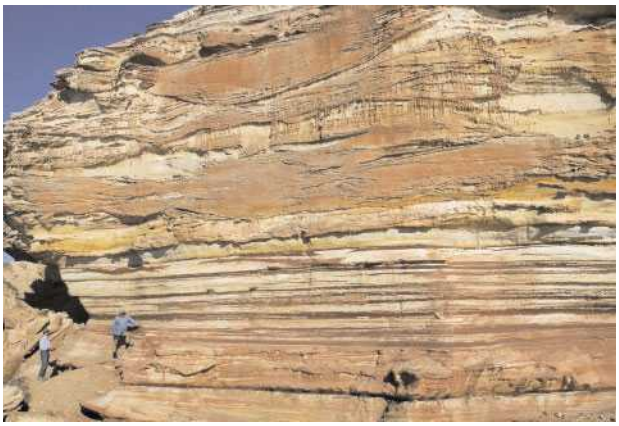

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Figure 7. Marine facies of the Tumblagooda Sandstone, Red Bluff (MGA 218030E 6927700N)

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. 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. 8)

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

Locality 3: Stone Wall, Murchison House Station

Summary: Good exposures of fluvial redbed facies of the Ordovician Tumblagooda Sandstone, overlain by Cretaceous Winning Group and Toolonga Calcilutite.

Location: About 18 km north-northeast of Kalbarri, MGA 228600E 6946600N, GANTHEAUME.

Access: Drive to Murchison House Homestead (off the Ajana–Kalbarri Road), cross the river at the station causeway, turn north after 800 m, just past a small duricrust outcrop, follow the track 8 km north, turn west on a prominent firebreak and drive 1 km along the south side of the gully. Park just below the outcrop of the Tumblagooda Sandstone with a low stone wall (MGA 229030E 6946520N) on it, and walk up the gully. Dual-range four-wheel drive is necessary past the homestead, and some sections of the track consist of very soft sand, so tyres may need to be deflated significantly. Contact Murchison House beforehand (08 9937 1998). The locality is listed with the National Estate as an 'indicative place' (Place ID: 18749).

Geology: The upper part of the Tumblagooda Sandstone (Fig. 9), and a Cretaceous section (Fig. 10) comprising the Birdrong Sandstone, Windalia Sandstone Member of the Muderong Shale, Windalia Radiolarite and Alinga Formation of the Winning Group, and the Toolonga Calcilutite are present in the creek and breakaways immediately above the springs at Stone Wall on the edge of the Pillawarra Plateau (Fig. 11).

The Tumblagooda Sandstone exposed here is primarily FA3 (Fig. 9). FA4 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

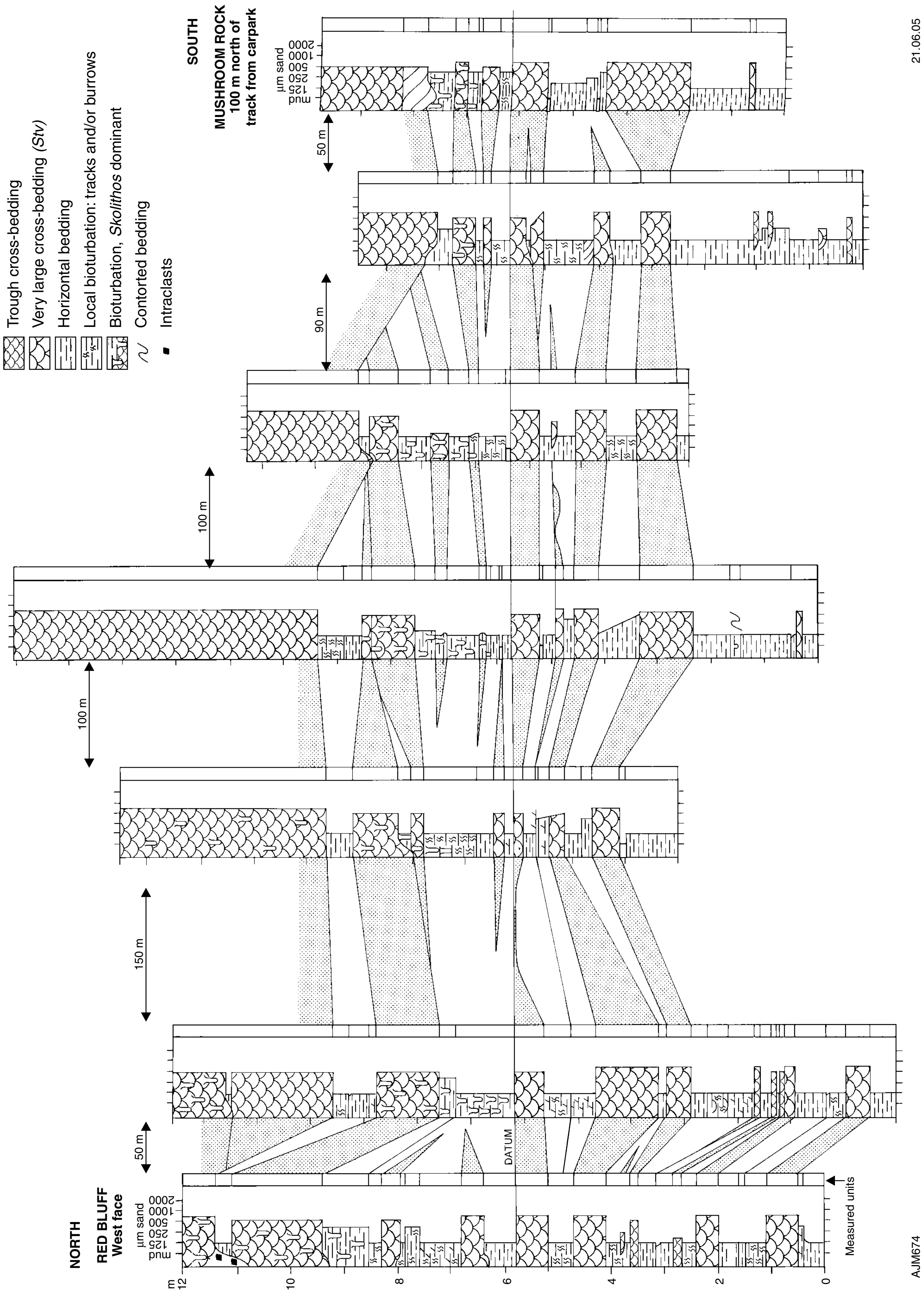

Figure 8. Measured sections through the Tumblagooda Sandstone, Red Bluff to Mushroom Rock (after Hocking, 1991). From MGA 218030E 6927700N to 217950E 6927060N

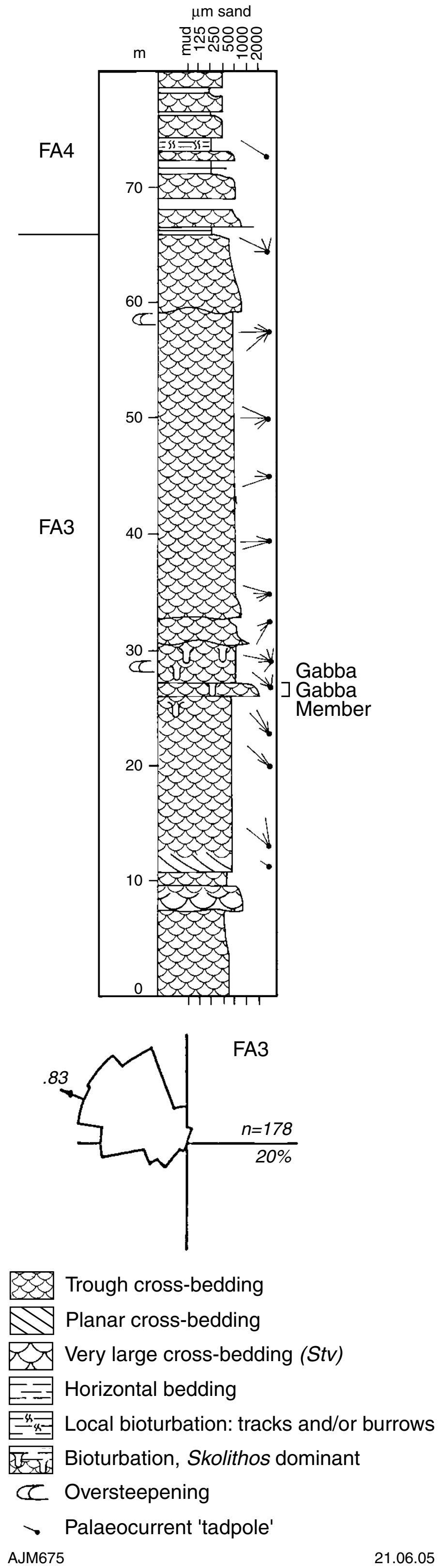

Figure 9. Measured section of the Tumblagooda Sandstone at Stone Wall (after Hocking, 2000; MGA 228940E 6946600N)

sandstone, and is typical of the upper part of FA3. The Gabba Gabba Member is about 20 m above the base of the section, just above the first terrace level. The lowest occurrence of scattered vertical burrows (*Cylindricum*) is 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 right-hand branch in the gully at the top of the Tumblagooda Sandstone has more continuous exposure of the basal part of the Cretaceous Birdrong Sandstone. The very poorly consolidated to unconsolidated, light-grey quartz sandstones are about 33 m thick. 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, glauconitic sandstone. Weakly silicified fossil wood with *Teredo* borings, and rare ammonites, have been found at the top of the sandstone, which is tentatively correlated with the Windalia Sandstone Member of the Muderong Shale. Below this level, deposition is assumed to have been in shoreface to coastal environments; the sequence does not have many environmentally diagnostic features. Numerous plesiosaur bones, sufficient for reconstruction of a skeleton, have been recovered from the top of the sandstone in the southern gullies at Stone Wall (Cruikshank and Long, 1997).

Beds of compact radiolarian mudstone that belong to the Windalia Radiolarite overlie the sandstone. These are distinguishable by their low density, and that they form minor bluffs in the section. There are excellent sections of both the Windalia Radiolarite and Alinga Formation in several gullies along the scarp of the Pillawarra Plateau toward Thirindine Point. The Windalia Radiolarite is up to 16 m thick and overlain, in turn, by friable glauconitic sandstone of the Albian part of the Alinga Formation, up to 6 m thick. The Cenomanian part of the Alinga Formation (about 1 m thick) consists of glauconitic claystone and is equivalent to the upper Gearle Siltstone elsewhere in the Southern Carnarvon Basin. Both the Alinga Formation and Windalia Radiolarite are low-energy, sub-wave-base, inner neritic deposits (Haig, 2005).

The Toolonga Calcilutite rests disconformably on the Alinga Formation. Phosphate nodules locally mark the contact. It is about 25 m thick and consists of very fossiliferous, white-weathering calcilutite and calcisiltite containing abundant small fragments of *Inoceramus*, a giant bivalve. 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 4: Yalthoo Field, Murchison House Station

Summary: Good exposures of friable shallow-marine facies of the Cretaceous Winning Group, Haycock Marl, and Toolonga Calcilutite in gullies and landslides; elsewhere exposures are very poor; type and reference sections of the Toolonga Calcilutite.

Figure 10. General view of the Cretaceous section at Stone Wall (MGA 228670E 6946450N)

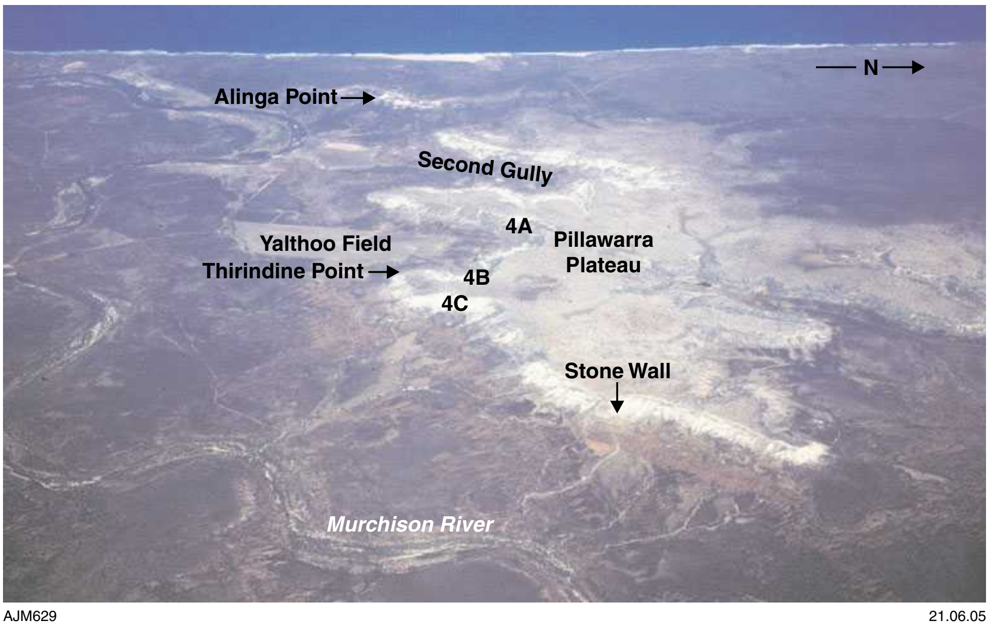

Figure 11. Oblique aerial photograph of Stone Wall to Yalthoo Field area

Location: About 14 km north-northeast of Kalbarri, MGA 225950–226950E 6943970N, GANTHEAUME.

Access: Drive about 5.5 km north of Murchison House Station Homestead on the four-wheel drive track to the shearing shed, and then either east or west along tracks adjacent to fences. The Cretaceous section (Table 3) is best exposed along the scarp of the Pillawarra Plateau at Localities 4A, 4B and 4C marked on Figure 11. Access to Localities 4A and 4B is by walking from the boundary fence across the low hills at the foot of the scarp. Locality 4C can be reached either by walking across the plateau top east of 4B or en route to Locality 3 (Stone Wall). Permission to enter this area must be obtained beforehand from Murchison House Station (08 9937 1998).

Geology: The stratigraphic section shows the marine transgressive cycles that affected the western Australian passive margin during the Barremian to Campanian. Locality 4A (Fig. 12a) includes the reference section of the Toolonga Calcilutite described by Lynch (1991). Three units of the formation are recognized here (Table 3). Units 1 and 2 make up the 'Toolonga Chalk' as described by Clarke and Teichert (1948), and unit 3 is equivalent to their 'Second Gully Shale'. Johnstone et al. (1958) combined the two formations as the Toolonga Calcilutite. At this locality the Toolonga Calcilutite ranges from Lower Santonian to Lower Campanian, and the section has attracted international interest as a possible reference for the boundary between these global stages (Gale et al., 1995). Of particular significance is the distribution of the crinoids *Uintacrinus* (from 2.5 to 5.5 m above the base of the section, according to Lynch, 1991) and *Marsupites* (extending 2 m immediately above *Uintacrinus*, according to Gale et al., 1995). The extinction of *Marsupites* has been suggested as a marker for the Santonian–Campanian boundary, and lies close to the boundary between units 2 and 3. The Toolonga Calcilutite contains abundant foraminifera (Belford, 1960). Figure 13 shows a correlation between the reference section of the Toolonga Calcilutite at Locality 4A and the type section of the Gingin Chalk, based on foraminiferal datum levels. The Toolonga Calcilutite at Locality 4A is underlain by poorly exposed Early to Middle Albian Alinga Formation.

Locality 4B (Fig. 12b) includes Clarke and Teichert's (1948) type section of the 'Toolonga Chalk'. The scarp at this locality is greatly affected by slumping of chalk, and the overlying unit 3 ('Second Gully Shale') is very weathered and poorly exposed. At the base of the section, upper beds of compact radiolarian mudstone that belong to the Windalia Radiolarite overlie sandstone. These beds are distinguishable by their low density, and that they form minor bluffs in the section. Excellent sections of both the Windalia Radiolarite and Alinga Formation are present in several gullies along the scarp of the Pillawarra Plateau toward Thirindine Point. The Windalia Radiolarite is up to 16 m thick and overlain, in turn, by friable glauconitic sandstone of the Albian Alinga Formation, up to 6 m thick. This correlates to the type section of the Alinga Formation at Alinga Point on the western side of Murchison House Station. The Cenomanian 'upper' Gearle Siltstone (about 1 m thick) consists of glauconitic claystone and is equivalent to the 'upper' Gearle Siltstone elsewhere in the Southern Carnarvon Basin. The Windalia Radiolarite is a low-energy, sub-wave-base, inner neritic deposit (Haig, 2005), whereas the Alinga Formation and Gearle Siltstone are mid-neritic deposits

Locality 4C on the eastern side of Thirindine Point (MGA 226950E 6943970N) includes a 31 m-thick section of Cretaceous sandstone overlying the Tumblagooda Sandstone. This section is interpreted as 16 m of Birdrong Sandstone, overlain by 15 m of the Windalia Sandstone

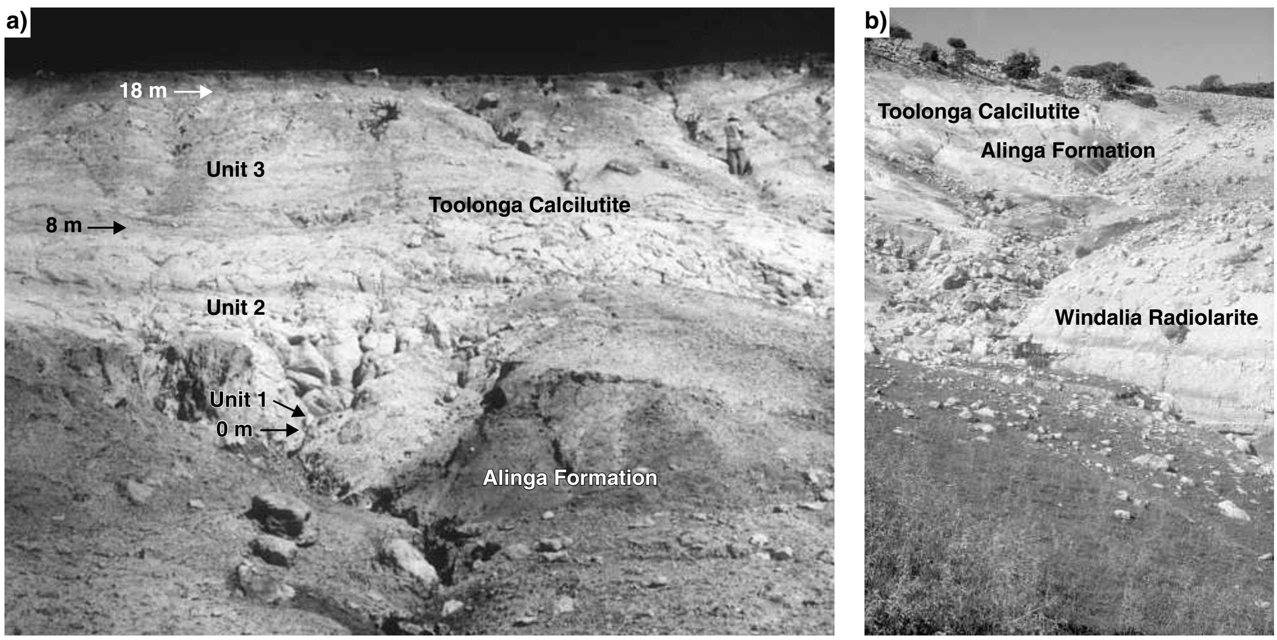

Figure 12. General views of the Cretaceous succession, Yalthoo Field area: a) Locality 4A (MGA 225950E 6943970N), b) Locality 4B (MGA 226400E 6943950N)

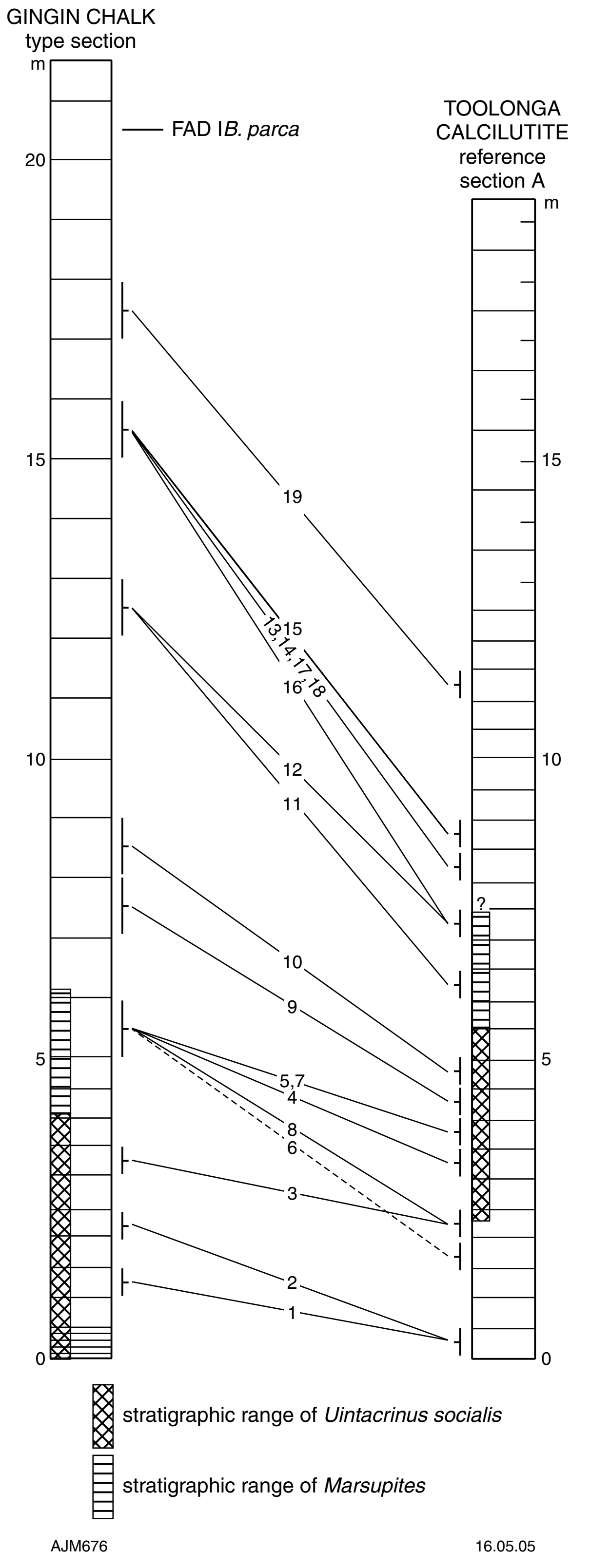

Figure 13. Correlation between the reference section of the Toolonga Reference section (Locality 4A; MGA 225950E 6943970N) and the type section of the Gingin Chalk (Locality 35; MGA 395650E 6534280N), based on foraminiferal datum levels. Datum levels are numbered 1–19 and include: 1, last appearance datum (LAD) *Stensiöina truncata*; 2, LAD *Valvulinoides*? sp.; 3, LAD *Clavulinoides trifidus*; 4, LAD *Anomalinoides undulatus*; 5, LAD *Marssonella* sp. cf. *M. ellisorae*; 6, first appearance datum (FAD) *Loxostomum eleyi*; 7, FAD *Cibicides excavata*; 8, FAD *Sliteria*? stellula; 9, FAD *Anomalinoides eriksdalensis*; 10, FAD *Notoplanulina* sp. 1; 11, LAD *Spiroplectina compressiuscula*; 12, FAD *Bolivinoides strigillata*; 13, FAD *Orectostomina*? *paula*; 14, FAD *Spiroplectammina grzybowskii*; 15, FAD *Bulimina triangularis*; 16, FAD *Sliteria*? *insculpta*; 17, LAD *Notoplanulina* sp. 1; 18, LAD *Sliteria*? *stellula*; 19, FAD *Neoflabellina praereticulata*. Nannofossil datum level, FAD *Broinsonia parca*, follows Shafik's (1990) records of the species (based on an analysis of close-spaced samples). The crinoid zonation follows Withers (1926) and Feldtmann (1963) for the Gingin Chalk type section, and Lynch (1991) and Gale et al. (1995) for Locality 4A

Member of the Muderong Shale (B. A. Taylor, written comm., 2005; Fig. 14). The upper part of the Windalia Sandstone Member contains rare, poorly preserved Aptian ammonites. Above this is an 11.5 m section of Windalia Radiolarite, then about 6 m of the Alinga Formation, which contains abundant vertebrate remains (Siverson, 1996). The upper Gearle Siltstone and Haycock Marl are thin discontinuous lenses between the Alinga Formation and Toolonga Calcilutite (e.g. at MGA 226950E, 6943970N).

Locality 5: 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, MGA 215900E 6921500N, GANTHEAUME.

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 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. 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 (Figs 15a and 16). Uppermost *Skolithos*-bearing sandstone beds are the best indicators of the top of the Ordovician section (Fig. 15b). 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 15a–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 outcrop of Perth Basin units on the coast.

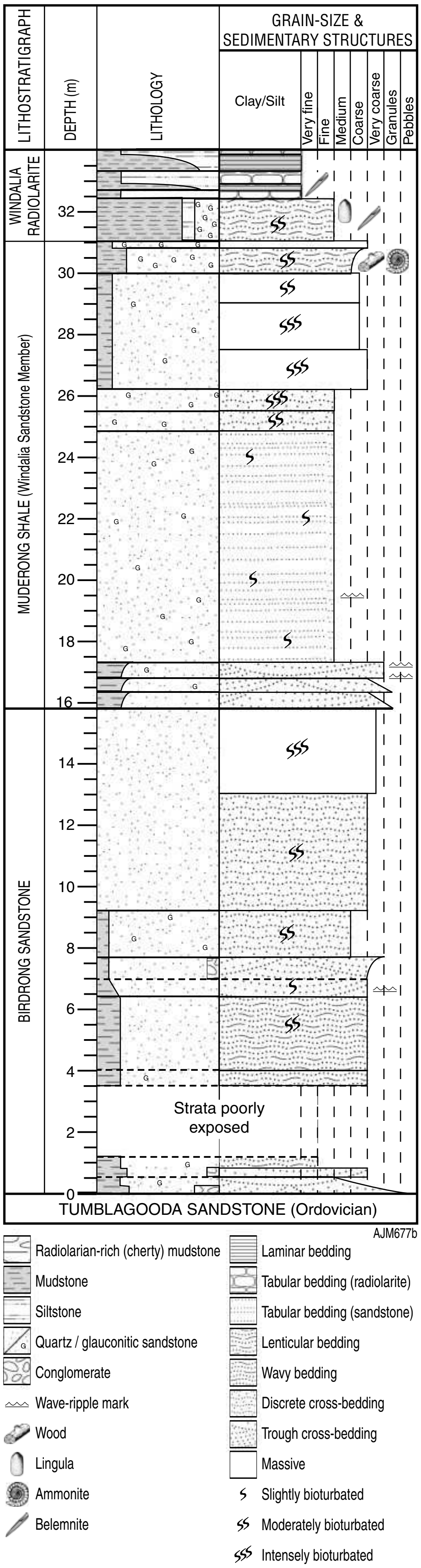

Figure 14. Basal Cretaceous sandstone, Thirindine Point (by B. A. Taylor; MGA 226950E 6943900N).

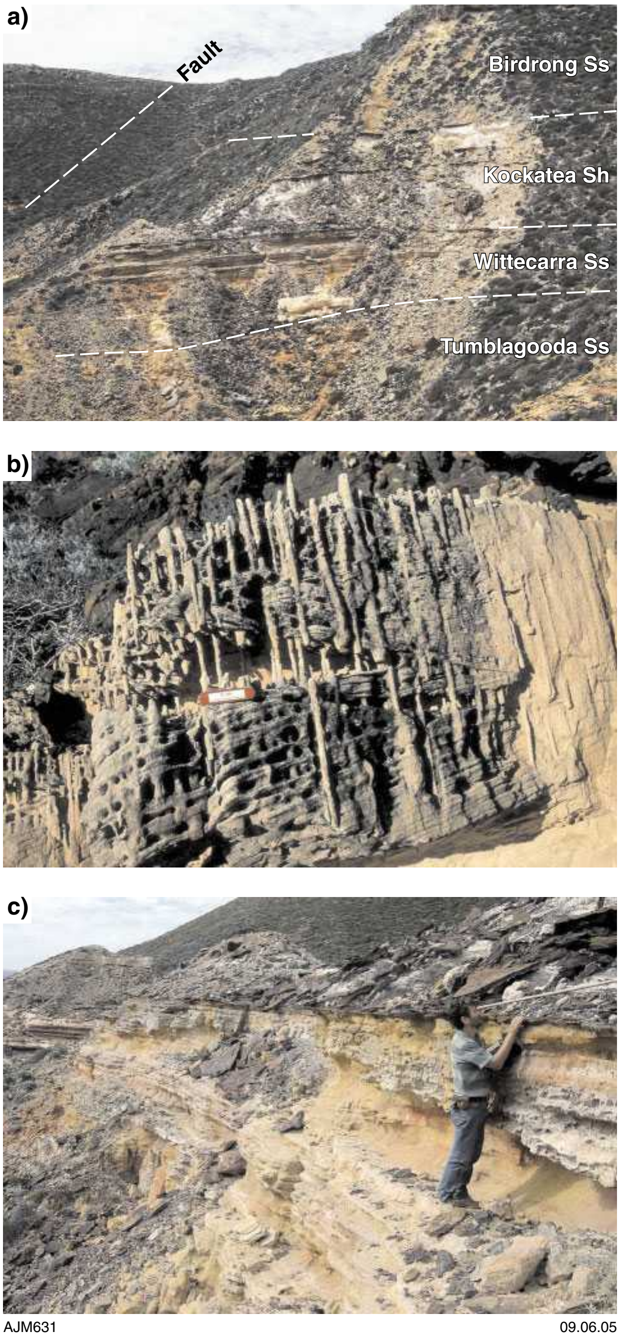

Figure 15. Shell House: a) Cretaceous and Triassic rocks overlying the Ordovician Tumblagooda Sandstone. Taken from MGA 216180E 6921500N; b) *Skolithos* bed in Tumblagooda Sandstone (MGA 216120E 6921680N); c) top of the type section of the Wittecarra Sandstone (MGA 216150E 6921600N). Contact with Kockatea Shale level with person's head (photograph by Richard Evans, Curtin University)

The Birdrong Sandstone mantles 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 a metre thick beneath the Tamala Limestone.

Locality 6: Pencell Pool, Murchison River

Summary: Good exposures of fluvial and tidal redbed facies of the Ordovician Tumblagooda Sandstone.

Location: About 60 km east of Kalbarri, MGA 283220E 6924240N, Ajana.

Access: Turn east off the North West Coastal Highway at Coolcalalaya Road (1.5 km south of the Galena Bridge over the Murchison River, or 12 km north of the turnoff to Kalbarri), and turn into 'Yandi' after 13.5 km. Turn left at the first gate and drive 600 m west around the edge of the paddock to the next gate, then drive 400 m west on a poorly marked track. Cross the river on the rock bar and walk downstream about 400 m. Note that the sand in the last 200 m may be difficult to drive over. The site is registered with the National Estate (Place ID: 19080). Contact Yandi Pastoral Company (Ajana 6532, ph. 08 9936 1020) regarding access.

Geology: A section of Tumblagooda Sandstone more than 200 m thick, and dipping at up to 32° towards the northeast, is exposed along the western bank of Pencell Pool, on the Murchison River between possible Permian strata further upstream and faulted against Mesoproterozoic gneisses of the Northampton Complex. These are exposed at Ten Mile Pool, 1 to 2 km to the southwest. The section is readily divisible into three units (Hocking, 1991): a lower unit of coarse-grained, trough cross-bedded sandstone; a middle unit of fine- to medium-grained sandstone; and an upper unit of coarse-grained, trough cross-bedded sandstone.

The lower unit is at least 20 m thick, and contains only coarse- to very coarse grained, brown and grey, medium- and large-scale trough cross-bedded sandstone with abundant granules and common small pebbles. There are larger troughs, up to 80 cm thick and several metres wide at regular intervals, but cyclicity is not obvious because of the nature of the outcrop. Palaeocurrent directions are northwestward, and the unit is separated from the base of the section at the south end of Pencell Pool by about 250 m of superficial cover (about 75 m stratigraphic thickness).

The middle unit consists of fine- to medium-grained, in part silty, bioturbated sandstone. Bedding within the unit is commonly indistinct because of bioturbation and weathering. Most of the unit is horizontally bedded, but planar and trough cross-bedding are also present. Much of the unit is featureless because of bioturbation, which has not left clear burrow outlines, unlike *Heimdallia* in FA2. The dominant recognizable burrow is *Skolithos*, and *Diplocraterion* is present in a few exposures (Fig. 17a). Cross-bedded intervals typically overlie horizontally bedded sandstone sharply but with little basal scouring, and contain *Skolithos*.

Fining-upward cyclicity can locally be distinguished in the middle unit. Cycles are 3 to 5 m thick, and grade from trough cross-bedded, *Skolithos*-bearing sandstone at the base; through horizontally bedded, bioturbated, medium- to fine-grained sandstone; to fine- to very fine

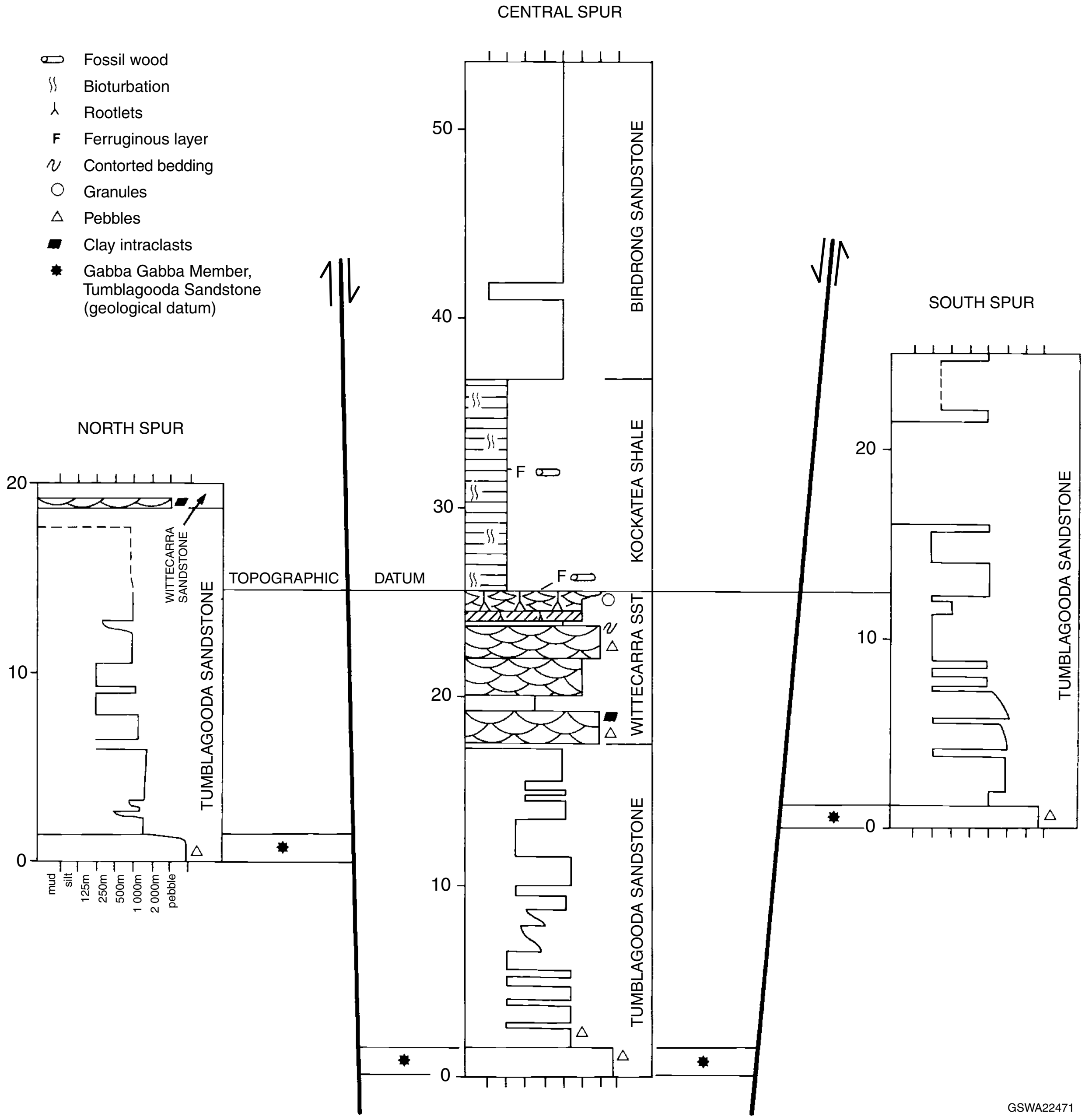

Figure 16. Measured sections showing the small graben at Shell House (after Hocking, 2000; from MGA 216180E 6921500N to 216180E 6921750N). See Figure 9 for key to bedding

grained bioturbated silty sandstone to sandy siltstone at the top (Fig. 17b). Thick, apparently non-cyclic, sequences are also present midway through the section downstream of the fence and bar.

The lower 30 m of the upper unit is intercalated with the underlying middle unit of the Pencell Pool sequence, just south of the rock bar and fence across the river. Non-bioturbated, trough cross-bedded sandstone gradually increases in abundance and grain size up section, to coarse- to very coarse grained, trough cross-bedded sandstone, similar to the lower unit. This coarsens upwards over 40 m into very coarse grained sandstone to granule conglomerate, and extends up the river valley for several hundred metres beyond the top of the exposures at Pencell Pool. Palaeocurrent directions are northwesterly, except in one group of northeast-facing troughs.

The strongly unimodal palaeocurrents, the poor sorting, and the scale and type of cross-bedding indicate that the lower and upper units were deposited in shallow, high energy, braided fluvial environments by low, three-dimensional dunes. The middle unit was deposited in protected marginal marine to nearshore conditions with longshore (broadly southwards) flow dominant. The intense bioturbation of much of the horizontally bedded facies, in which bedding has commonly been obliterated, probably arose through relatively continuous slow deposition or discontinuous deposition. This regime was interrupted by more energetic events, which deposited the less-bioturbated cross-bedded

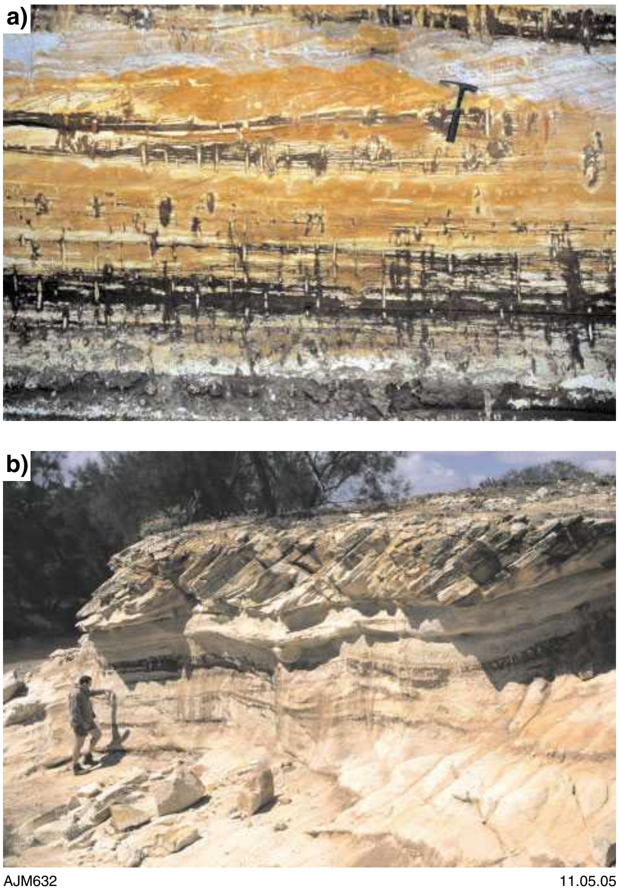

Figure 17. Tumblagooda Sandstone, Pencell Pool showing a) *Skolithos* (MGA 283250E 6924175N), and b) small cross-beds in marine facies (MGA 283220E 6924240N)

intervals in either subaqueous channels or migrating shoals.

Of the Tumblagooda Sandstone section in the river and coastal gorges, the middle unit at Pencell Pool is most similar to the upper section in the coastal gorges (FA4). Both are characterized by abundant *Skolithos*, both show regular interbedding of trough cross-bedded sandstone and finer, bioturbated sediments, and neither contains *Heimdallia* sp., the most abundant trace fossil in FA2 as at the Z Bend. The lower unit at Pencell Pool probably correlates with the upper fluvial interval in the river gorges, as there are scattered exposures on Riverside Station that underlie the Pencell Pool succession and are similar to FA2, the tidal association in the river gorges.

Northampton area

Background geology

Ordovician, Lower Triassic, Lower Jurassic, and minor Lower Cretaceous strata are exposed west of the gneiss and granulite of the Northampton Complex. All these strata are essentially flat lying, and the large breaks in deposition are deduced from stratigraphic correlations and limited palaeontological evidence. The Ordovician facies are mostly fluvial, with tidal deposits like those of FA2 near Horrocks, and appear to be progressively younger southwards, so that the southernmost exposures resemble FA3 rather than FA1. The overlying Lower Triassic Kockatea Shale is widespread, but is mostly poorly exposed, typical of shale-dominated units in Western Australia, apart from where sandy facies are present. Lower Jurassic sandstone of the Chapman Group forms the higher hills in the area, where they disconformably cap the Lower Triassic. These units are discussed in more detail under **Geraldton area** below. Cretaceous strata are limited to low exposures of the Windalia Radiolarite that extend south to near the intersection of Yerina Spring and Olgive Roads, northeast of Hutt Lagoon, and are discussed in more detail under **Kalbarri area**. Moulds of belemnite cones are common in places.

Locality 7: Blue Hills

Summary: Good exposures of Lower Triassic shallow marine siltstone of the Kockatea Shale, containing basal stromatolites, disconformably overlying fluvial facies of the Ordovician Tumblagooda Sandstone.

Location: About 13 km west of Northampton, MGA 254720E 6860290N, Hutt.

Access: Drive towards Horrocks Beach from Northampton. Turn north onto Nanson Road off the Horrocks Beach Road, then after 800 m turn west and drive 4 km on Suckling Road to ‘Blue Hills’. Walk south, across or around the paddock, to the breakaway. Contact E. and K. Suckling (‘Blue Hills’ Horrocks 6535, ph. 08 9934 3026) for access.

Geology: In the gully south of the road, a stromatolite bed at the base of the Lower Triassic Kockatea Shale overlies pebbly cross-bedded sandstone of the Tumblagooda Sandstone. The bed is strongly ferruginized and contains stromatolites either encrusted onto clean sandstone surfaces (upper beds of Tumblagooda Sandstone), or onto pebbles on the Tumblagooda erosion surface. The latter imply an Early Triassic wave-cut platform in places strewn with pebbles. Growth forms developed in the stromatolites include low, flat encrustations on the underlying rock, broad domal structures up to 50 cm across, pillars several centimetres in width, and digitate forms with thin columns (each about 0.5 cm in width; Fig. 18). Small nodules are developed on the surfaces of some of the domes. In places there are a succession of growth forms, from flat encrustations or broad domes, pillars to digitate columns, which are similar to those at Locality 32, Lake Thetis, Cervantes. Repetitions of this growth cycle, or various parts of it, are also present. The stromatolitic layer is generally less than 20 cm thick, and is here tentatively correlated with the upper part of the Hovea Member described by Thomas and Barber (2004) and Thomas et al. (2004).

The stromatolitic bed is overlain by laminated mudstone with thin fine-grained sandstone interbeds covered by a range of small burrow types, although this is difficult to see in the friable leached rock. A thin layer of

a)

b)

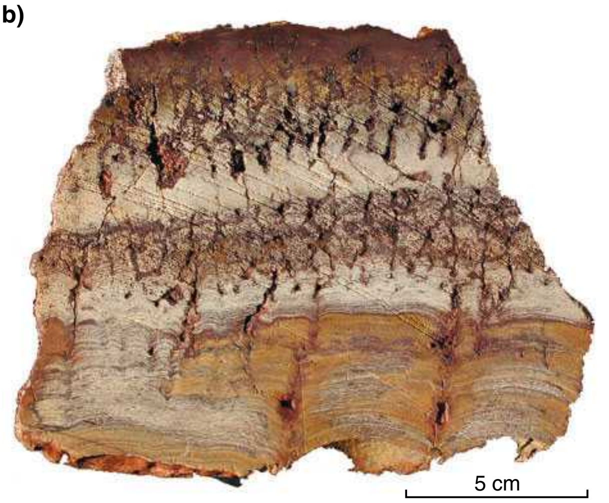

Figure 18. Small stromatolites from base Kockatea Shale, Blue Hills. Collected from; a) MGA 254740E 6860500N, b) MGA 254055E 6860515N

the mud containing small trace fossils is cemented to the sandstone surface by reddish iron oxides. The ichnofauna has not been studied in any detail.

Thin cross-laminated sandstone beds are more abundant higher in the succession and ammonoid moulds are sparsely scattered on some bedding surfaces. The ammonoids are similar to those described by Skwarko and Kummel (1974) from north of Blue Hills, and are attributed to the Griesbachian–Smithian (Induan–Olenekian of Gradstein et al., 2004). The precise age of the stromatolite bed is uncertain. Playford et al. (1976) lists the relatively few species of brachiopods, bivalves, nautiloids, ammonoids, annelids, ostracodes, conodonts, vertebrates, and palynomorphs that have been recorded from the formation elsewhere in the northern Perth Basin (mostly from boreholes).

On the south face of the next gully to the south (MGA 254600E 6860160N), the Tumblagooda Sandstone is cut by a 330°-striking fault, part of which has been infilled by finer grained material, and so may have initiated as an extensional fracture and clastic dyke. Dextral displacement (post-lithification) is shown by steps along the slickensided fault plane with horizontal striations, and by a Riedel shear array. This structure indicates north–south compression pre-dating the overlying Lower Triassic Kockatea Shale.

Additional exposures of the Kockatea Shale showing the discontinuous stromatolitic layer are in a roadside outcrop approximately 1 km west of the gully (at MGA 254055E 6860515N) and in the paddocks to the south.

Locality 8: Mount Minchin

Summary: Good exposures of Lower Triassic shallow-marine sandstone facies of the Kockatea Shale.

Location: About 16 km northwest of Northampton, MGA 254200E 6870375N, Hutt.

Access: About 500 m southeast of the intersection of Swamp and Rob Road, 5 km north of Port Gregory Road. Turn west from Swamp Road, about 300 m south of the intersection of Swamp and Rob Road, and drive along edge of the paddock to the southeast side of Mount Minchin. Walk over the saddle to the northwest side of the pinnacle (informally known as Sugarloaf Hill), which is clearly visible from the Port Gregory Road. Contact CMD Equities (ph. 08 6267 9038) regarding access.

Geology: Approximately 20 m of Kockatea Shale is exposed as flat-lying strata in Sugarloaf Hill, with an additional 10 m to the north on Mount Minchin (Fig. 19a). Trails, burrows, and various tool marks are outlined on bedding surfaces especially near the prominent large undulose asymmetric ripples on the northwestern side of the saddle between Mount Minchin and Sugarloaf Hill. In cross section, the asymmetrical ripples modify bedding similar to small-scale hummocky cross-stratification (Fig. 19b and c). The facies are similar to those of the Arranoo Member of the Kockatea Shale. The exposure is the type section of the 'Minchin Siltstone' of Johnson and Playford (in McWhae, 1958) that was originally considered to be Lower Jurassic, as it appeared to lie conformably below the Greenough Sandstone in this region; however, the unit was abandoned in favour of the Kockatea Shale after Edgell (1964a) described Owenitian (lower Olenekian of Gradstein et al., 2004) ammonoid impressions about 2 m below the prominent rippled bed. This age is similar to the Smithian (late Early Triassic) age suggested by Skwarko and Kummel (1974). A shallow, restricted-marine environment is likely, based on the limited fauna and sedimentary structures.

Locality 9: Yallabatharra Road, Hutt River

Summary: Road cutting through a small anticline in Lower Triassic shallow-marine sandstone facies of the Kockatea Shale.

Location: Road cutting about 24 km northwest of Northampton, MGA 247250E 6874100N, Hutt.

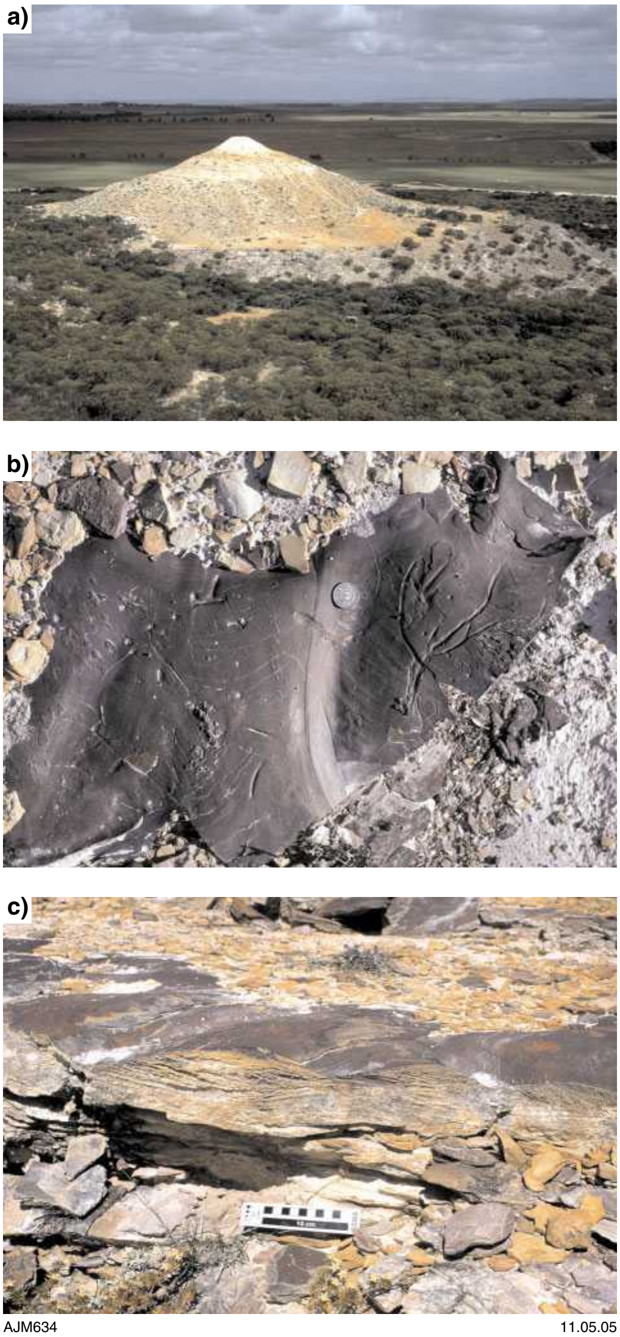

Figure 19. Kockatea Shale, Mount Minchin (MGA 254200E 6870375N): a) view from north; b) rippled surface showing crawling traces; c) hummocky bed modified by large ripples

Access: On Yallabatharra Road, about 5.8 km east of Northampton – Port Gregory Road or 6.8 m west of Swamp Road.

Geology: A small anticline in the Kockatea Shale is exposed in the road cutting (Fig. 20a) in an area otherwise characterized by flat dips. The section is dominated by fine- to medium-grained sandstone containing large undulose asymmetric ripples and structures similar to hummocky cross stratification but without the erosive bases (Fig. 20b), as well as trails, burrows, and various tool markings on some bedding planes. A small number of ammonoid moulds have been found at this locality, and are similar to other faunas of late Early Triassic age in the area (Skwarko and Kummel, 1974). The facies are similar to the Arranoo Member of the Kockatea Shale in Dongara 24 (cores 4–9).

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

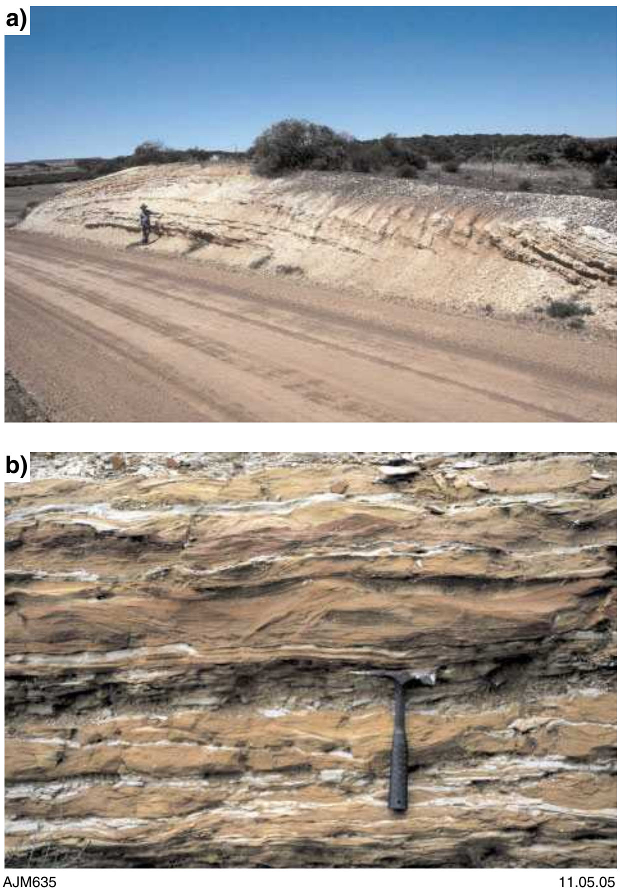

Figure 20. Kockatea Shale, Yallabatharra Road cutting (MGA 247250E 6874100N): a) small anticline; b) hummocky cross stratification in Kockatea Shale

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 mid- 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 14).

Locality 10: Bindoo Spring, Greenough River

Summary: Low riverbank cliff showing dropstones in fine-grained, glacio-marine, ?mid-Carboniferous to Lower Permian Nangetty Formation.

Location: About 30 km west of Mullewa, MGA 324880E 6846680N, MUNGO.

Access: Walk about 300 m southwest to bluff from car park, signposted on the Tenindewa Road as 'Glacier Bed', about 7.5 km north of Brenkley Road. The site is on a public reserve so permission for access is unnecessary. Do not collect samples as the site is registered with the National Estate (Place ID: 18740).

Geology: The 8 m-high cliff belongs within the mid-Carboniferous to Lower Permian Nangetty Formation although its precise position within the unit is uncertain. The section contains erratic Precambrian pebbles and boulders scattered through a poorly sorted sandy silty matrix with crude near-horizontal bedding (Fig. 21). Some of the boulders and larger pebbles show facets and striations related to transportation by ice. The most easily recognized erratics are derived from the Yandanooka and Moora Groups, the nearest exposures of which lie 100 to 250 km to the south-southeast, and some are from the Tumblagooda Sandstone (Playford et al., 1976). Most of the larger boulders are no longer in situ.

Two kilometres northeast, on a low ridge 60 m south of Williamson Road (at MGA 325960E 6848095N), two striated bedding surfaces indicate ice movement to the north-northwest penecontemporaneous with sand deposition (Fig. 22). The relationship of this outcrop with that north of Williamson Road, previously mapped as Tumblagooda Sandstone, is unknown. As with the exposure at Bindoo Spring, the age of this section and its position in the Nangetty Formation is unclear.

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Figure 21. Glacial deposit, Nangetty Formation, Bindoo Spring (MGA 324880E 6846680N)

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Figure 22. Glacial striae, Nangetty Formation, 2 km northeast of Bindoo Spring (MGA 325960E 6848095N)

Locality 11: 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, MGA 329350E 6839915N, INDARRA.

Access: Walk west into gully about 300 m south of the junction of Brenkley Road with Tenindewa Road. Contact K. Weir (c/- P.O. Tenindewa, 6632, or ph. 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. 23). 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.

Locality 12: Badgedong Creek – Wooderarrung River

Summary: Long exposure on riverbank showing coarse-grained channel-fill facies of ?mid-Carboniferous to Lower Permian Nangetty Formation.

Location: About 18 km northwest of Mullewa, MGA 345210E 6856450N, MUNGO.

Access: Turn west off Nubberoo Road at MGA 351300E 6856060N and drive 6.3 km west, and either cross the Wooderarrung River at MGA 345160E 6855480N and proceed 1 km north along west side of the fence, or park and walk downstream if in a two-wheel drive vehicle. The outcrop extends for over 300 m on the east bank. For photography, the site is best visited before late afternoon to avoid excessive glare from the white rock faces. There are also exposures worth visiting 300 to 500 m up Badgedong Creek, which joins Wooderarrung River 250 m downstream from this outcrop. Contact 'Daisy Downs' (Manager, K. Thompson, ph. 08 9961 1018) regarding access.

Geology: Along the Wooderarrung River and in Badgedong Creek, mixed sandstone and conglomerate facies are exposed in channels, up to 100 m wide and 3 m deep, with erosional bases. The channels cut through flat-lying pebbly sandstone (Figs 24 and 25). The outcrop shows lateral channel avulsion and accretion from south to north. Deeply incised and narrow 'feeder channels' in Badgedong Creek are filled with poorly sorted conglomerate, sandstone and pebbly sandstone. In general, the coarser grained the sediment, the narrower and more deeply incised the channel. Typically, massive or crudely stratified conglomerate at the base of channels is overlain by sheet-like beds of massive, graded, and horizontally laminated or ripple cross-laminated sandstone. There are large clasts in the channel fills, but these are preferentially concentrated as lag-like horizons at the base of individual channels in places. A single outsized quartzite boulder, 1 m across, at the base of the southern flank of the largest channel may be a remnant from an episode of extremely high flow rates in the channel. Palaeocurrents are predominantly to the north, parallel to the strike of the basin margin and the Darling Fault. The facies are interpreted as glacial deposits, originally from a nearshore setting with a strong fluvial input, reworked into somewhat deeper water.

Locality 13: Nangerwalla Creek

Summary: Small cliff on bank showing glacio-marine, fine-grained sandstone facies of the ?mid-Carboniferous to Lower Permian Nangetty Formation.

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Figure 23. Glacial deposit, Nangetty Formation, Kockatea Gully (MGA 329350E 6839915N)

Figure 24. Panorama of glacial deposit, Nangetty Formation, Wooderarrung River (MGA 345210E 6856450N). Compressed 50% horizontally

Location: About 23 km north-northwest of Mullewa, MGA 347870E 6864330N, MUNGO.

Access: Drive about 1 km west of 'Daisy Downs' (Manager, K. Thompson, ph. 08 9961 1018) on Nubberoo Road, and proceed northeast through the gates at MGA 348010E 6862940N, past the shed to the edge of the creek. It may be necessary to walk about 1 km if the paddock is under cultivation.

Geology: The section contains thin-bedded, mostly rippled and laminated, fine- to medium-grained sandstone with minor thin massive beds. At the western end of the exposure a cross-bedded sandstone cuts a massive bed. Minor erosive contacts within this exposure indicate channel avulsion (Fig. 26) within an unstable shallow-marine setting. The entire section along Nangerwalla Creek is likely to be mid- to Upper Carboniferous based on palynomorphs from a water bore 4.5 km to the west-northwest (Backhouse, 1998).

Locality 14: Wenmillia Creek – Wooderarrung River

Summary: Long section with moderate exposures on banks of glacio-marine conglomerate, sandstone, and siltstone facies of the ?mid-Carboniferous to Lower Permian Nangetty Formation.

Location: About 7 km northwest of Mullewa, from MGA 350270E 6848880N to MGA 349740E 6848540N, MUNGO.

Access: Turn off Nubberoo Road at MGA 351400E 6848660N just south of Wenmillia Creek and follow

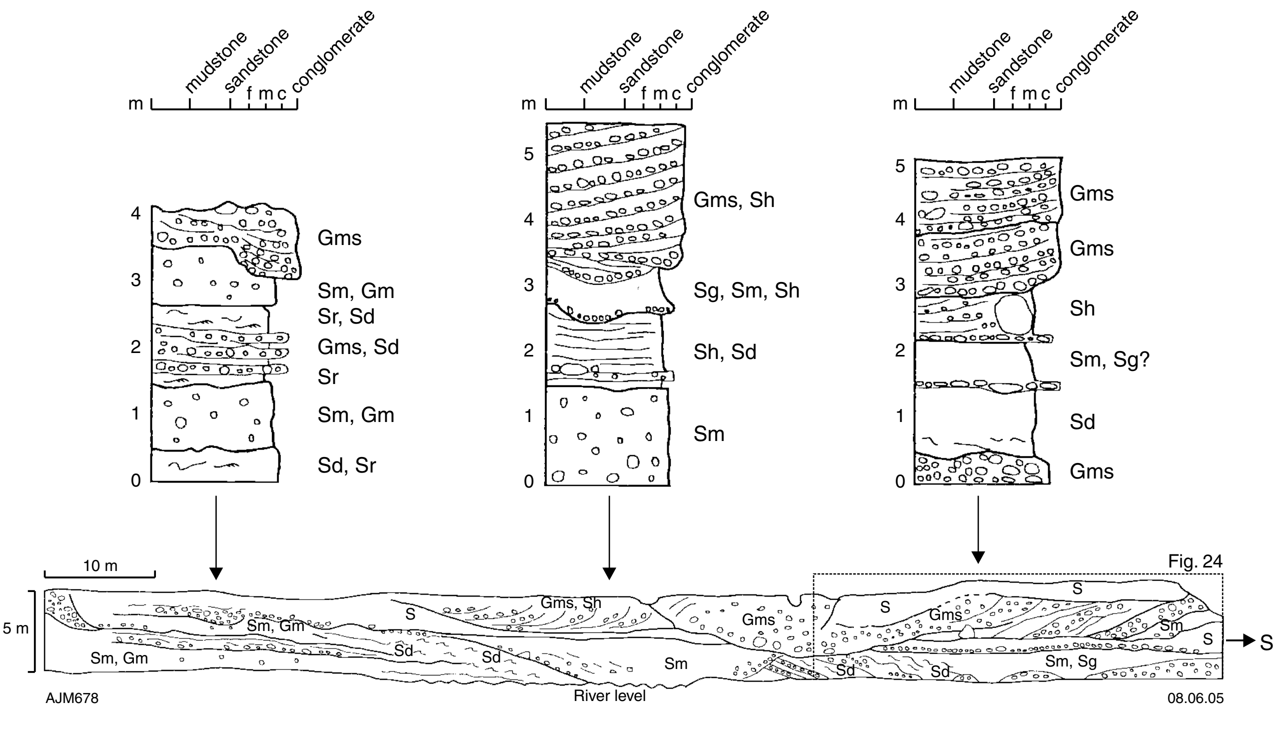

Figure 25. Measured sections of Nangetty Formation, Wooderarrung River (MGA 345210E 6856450N). See Figure 27 for code to facies. After Eyles et al. (in prep.)

Figure 26. Panorama showing channel avulsion in Nangetty Formation, Nangerwalla Creek (MGA 347870E 6864330N). Hammer (circled) for scale

the farm track southwest to Wooderarrung River. Contact 'Daisy Downs' (Manager, K. Thompson, ph. 08 9961 1018) beforehand.

Geology: A moderately long section of interbedded massive and rippled sandstone and conglomerate facies containing faceted and striated boulders, and capped by laminated siltstone and mudstone, is exposed along Wenmillia Creek, starting from the Darling Fault and continuing upstream about 600 m in the Wooderarrung River (Fig. 27) to a prominent exposure of laminated siltstone and mudstone (Fig. 28), previously described as varves (Playford et al., 1976). Laminations are between 1 and 3 cm thick, and consist predominantly of alternations of siltstone and mudstone but also contain thin horizons of diamictite, conglomerate, and horizontally laminated and graded sandstone. These laminated facies are mostly flat lying but discrete horizons, up to 1 m thick, are extensively slump folded. Rare outsized clasts (up to 5 cm diameter) are in the mudstone exposed further downstream and at Bindoo Springs (Playford and Willmott, 1958). The laminated facies have been previously referred to as varves, but could also be distal turbidites, whereas the sandstone and conglomerate facies are akin to sandy proximal mass-flow deposits.

Approximately 500 m downstream from the junction of Wenmillia Creek with the Wooderarrung River, slumped sandstone beds characterized by large folds and dewatering structures are well exposed on the west bank of the river (Fig. 29). Alternately, this outcrop (MGA 348750E 6849900N) can be reached from Sutherland Road en route to Wootbeeria Pool on the Wooderarrung River. Playford et al. (1976, fig. 19) explains this exposure as 'grounding of an iceberg or ice flow on unconsolidated sediments'. Slumping has affected both individual beds (approximately 30 to 50 cm thick) and composite units up to 5 m thick.

Locality 15: Wootbeeria Pool, Wooderarrung River

Summary: Good cliff section showing sandstone diamictite and channel-fill facies in the ?mid-Carboniferous to Lower Permian Nangetty Formation.

Location: About 12 km northwest of Mullewa, MGA 348370E 6848890N, MUNGO.

Access: Drive though the gate at the north end of Sutherland Road, turn left at the shed and continue along the farm track. Turn north at MGA 346100E 6850720N, pass the water tank at MGA 346110E 6851590N, cross a gully, and drive along the edge of the paddock until opposite the white cliff. Contact B. Lynch (24 Fry St, Mullewa, 6630, ph. 08 9961 1047 or 08 9961 1178) beforehand.

Geology: The cliff exposes strongly contorted and massive pebbly sandstone facies overlain by flat-lying massive and cross-bedded medium-grained sandstone, possibly representing a channel fill (Fig. 30). The association of graded and massive sandstone, and poorly sorted pebbly sandstone is strong evidence for an energetic subaqueous setting where coarse-grained sediment was transported by sediment gravity-flow processes. Massive, graded and crudely stratified facies are identified as the product of coarse-grained turbidity currents (such as in Nemec et al., 1984). The presence of slumped facies overlain or incised by channels implies that downslope sediment gravity-flows may have been restricted to topographic lows created by the slumping.

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

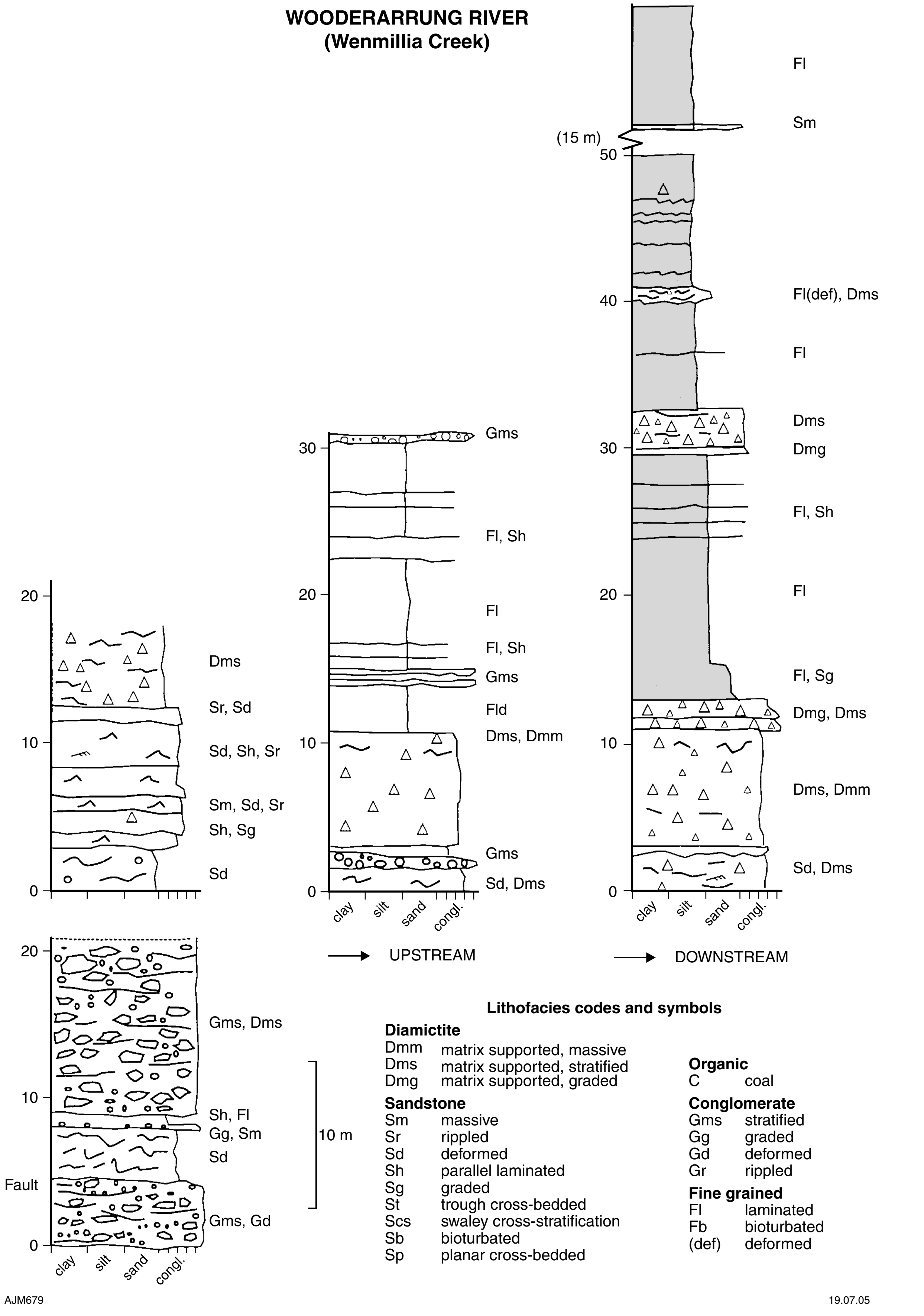

Figure 27. Measured sections of Nangetty Formation, Wenmillia Creek – Wooderarrung River (from MGA 350270E 6848880N to 349740E 6848540N). After Eyles et al. (in prep.)

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Figure 28. Laminated siltstone and claystone, Nangetty Formation, Wooderarrung River (MGA 349740E 6848540N)

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Figure 29. Contorted bedding in diamictite, Nangetty Formation, Wooderarrung River (MGA 348750E 6849900N)

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Figure 30. Massive to crudely cross-bedded facies overlying contorted diamictite, Nangetty Formation, Wootbeeria Pool (MGA 348370E 6848890N). Hammer (circled) for scale

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 P. E. 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 (Table 4). 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 16: Bringo

Summary: Rail cutting showing complete section of Middle Jurassic shallow-marine facies of the Champion Bay Group (including type sections of Bringo Shale and Kojarena Sandstone) sitting on basement, and a reference section of the Upper Jurassic Yarragadee Formation containing a small faulted anticline.

Location: Rail cutting about 24 km east of Geraldton, basement: MGA 289860E 6818000N; anticline: MGA 290100E 6818760N, GERALDTON.

Access: Turn east off the Geraldton – Mount Magnet Road 150 m south of the turnoff to the Bringo tennis courts (MGA 290100E 6818950N) and park 200 m south on the side road to view the anticline. To access the southwestern end of the cutting, turn east off the main road near the base of the hill at MGA 289040E 6818460 and take the second track to the south. The two turnoffs are on the old route of the main road and are connected. Note that the railway line is presently (2005) used all year to freight iron ore from Tallering, north of Mullewa. Approval and the conditions to enter the cutting must be sought a week beforehand from WestNet Rail by contacting the Per Way Superintendent's office at Narngulu (ph. 08 9964 0332). The locality is registered with the National Estate (Place ID: 18171).

Geology: Jurassic units onlap basement rocks of the Northampton Complex in the Bringo area. The clearest exposures are along the southern face of the cutting (Fig. 31) as described by P. E. Playford (1959, figs 53 and 56). The cutting has deteriorated markedly since 1997 when it was cut back at a low angle and is now partially covered in scree. The northern face illustrated by Campbell (1910, fig. 6, plate IV) is now almost entirely covered with scree and vegetation. The basement is composed of highly kaolinized, garnet-rich migmatite that contains remnants of a metamorphic fabric as xenoliths and partly assimilated bands of granulite. The gneissic banding dips east, forming the eastern limb of a regional anticline in basement rocks (GSWA, 1970). Striated, south-dipping reverse faults in the

Table 4. Stratigraphic units in Bringo cutting (sourced in part from Playford, P. E., 1959; Playford et al., 1976)

Age	*Group*	*Formation*	*Thickness*	*Description*
Late Jurassic (based on palynomorphs from subsurface)	–	Yarragadee Formation	16 m in cutting	interbedded poorly sorted sandstone and siltstone, minor shale and conglomerate, mottled red, yellow, and white in weathered exposures
Early Bajocian – Middle Jurassic (*ovalis/laeviuscala* ammonite zones; Hall, 1989)	Champion Bay Group	Kojarena Sandstone	10 m	ferruginous, medium- to coarse-grained sandstone, basal 0.6 m thick greyish white claystone in cutting
		Newmarracarra Limestone	up to 10 m nearby	bioclastic limestone, leached and replaced by iron oxide in the cutting, biota includes bivalves (>50 species), gastropods (>13), ammonoids (22), nautiloids (1), belemnites (3), brachiopods (>2), annelids (>2), echinoids (1), bryozoa (1), foraminifera (46), and ostracods (6)
		Bringo Shale	2.1 m	friable black shale containing palynomorphs, foraminifera (11 species), and vertebrate remains
		Colalura Sandstone	<0.5 m	friable, ferruginous, conglomeratic sandstone (originally a shelly limestone before weathering)
?Early Jurassic	Chapman Group	Moonyoonooka Sandstone	<1 m	fine- to very fine grained quartz and feldspar sandstone, locally with basal sandy conglomerate
Precambrian	–	basement	–	

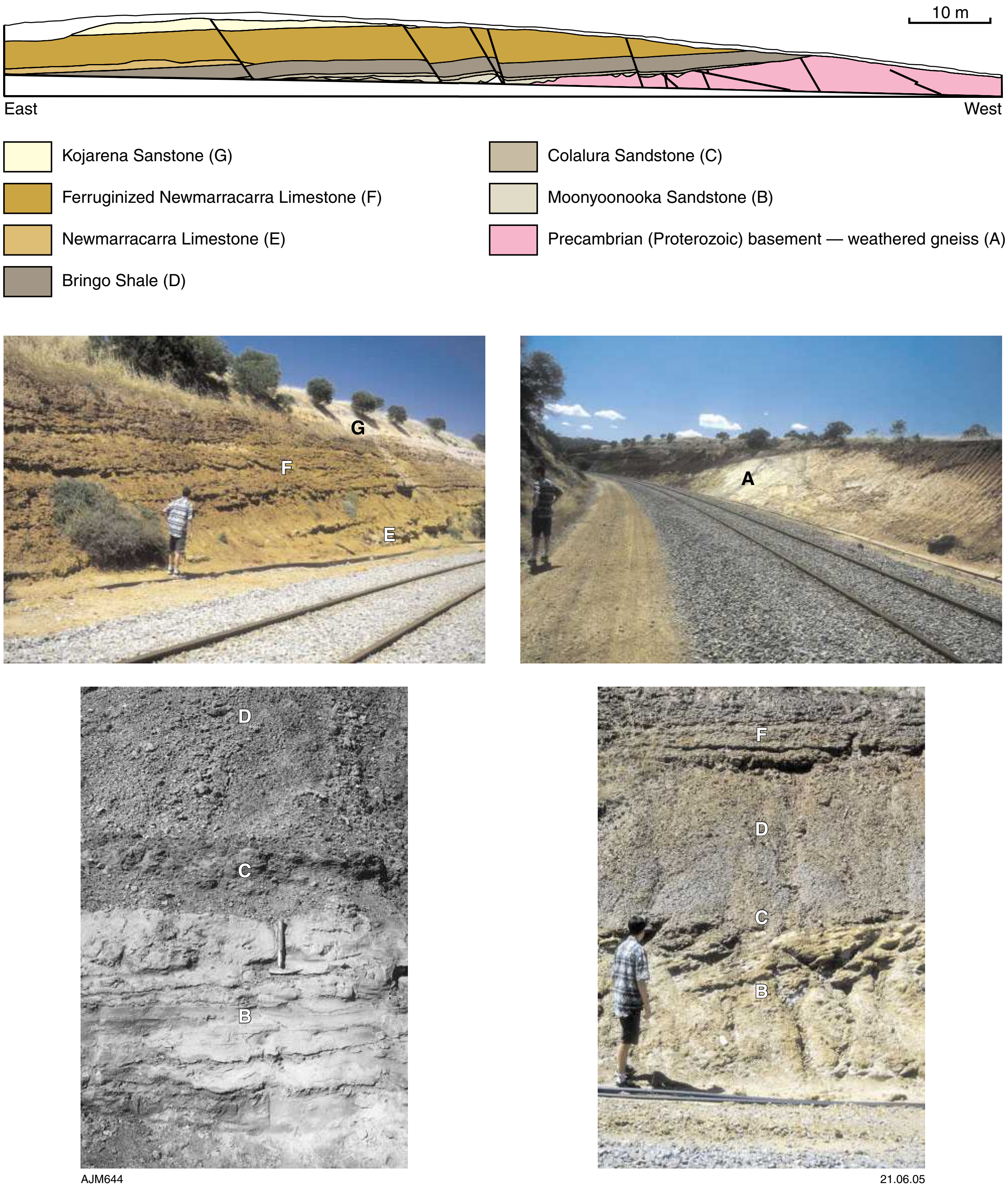

Figure 31. Jurassic Champion Bay Group onlapping basement, Bringo cutting (MGA 289860E 6818000N)

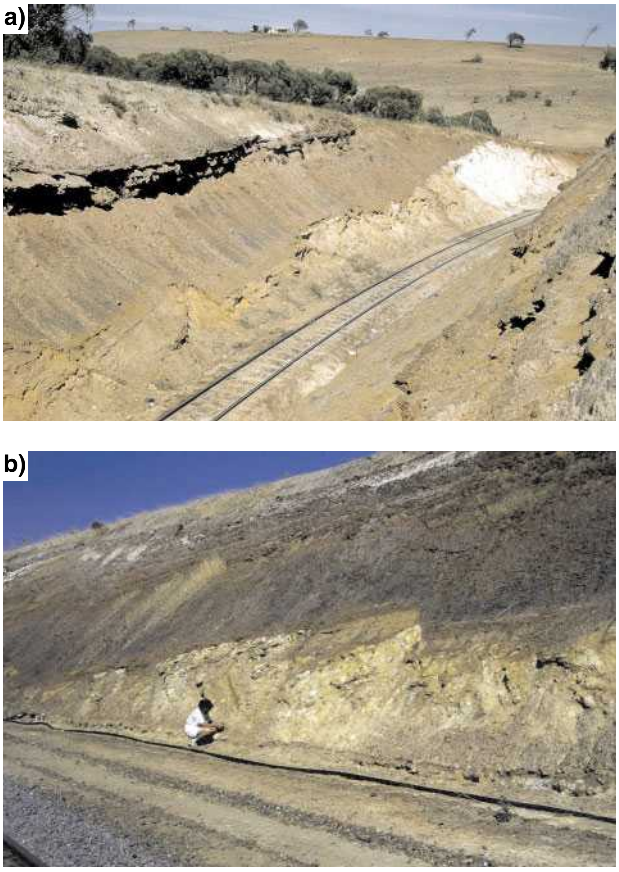

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Figure 32. Small faults intersecting mid-Jurassic strata and basement, Bringo cutting: a) general view taken in 1952 by P. E. Playford; b) detail of small faults and Moonyoonooka Sandstone disconformably overlying basement taken in 1998 (MGA 289860E 6818000N)

basement are overlain by the Jurassic Greenough Sandstone, indicating pre-depositional displacements (Fig. 32).

All units of the Champion Bay Group are exposed in the cutting. The group represents a short-lived Bajocian (Middle Jurassic; based on ammonites described by Arkell and Playford, 1954; Hall, 1989) transgression by a shallow sea. At this locality the unit, which is coeval with the Cadda Formation to the south, is approximately 18 m thick. At the base of the section, 1.5 m of feldspathic sandstone, assigned to the Moonyoonooka Sandstone, infills scours in the basement gneiss. Overlying it, above a planar unconformity, is approximately 0.5 m of Colalura Sandstone with phosphate nodules, fossil wood, leached shell debris and rare plesiosaur remains (Long and Cruickshank, 1998). This is overlain by 2 m of Bringo Shale, here consisting of black shale with thin yellow phosphate bands that was deposited in anoxic marine conditions. The Bringo Shale has an irregular distribution in the Geraldton area. The Colalura Sandstone and Bringo Shale represent an early transgressive phase in the deposition of the Champion Bay Group. The overlying Newmarracarra Limestone consists of approximately 5 m of crudely bedded sandy bioclastic limestone, and marks the maximum extent of the transgression. It is mostly leached of carbonate material in the cutting, but some unaltered limestone is at the eastern end of the exposure. The Kojarena Sandstone is a well-sorted, ferruginous sandstone that conformably overlies the Newmarracarra Limestone. This contact may be interpreted as a downlap surface with the Kojarena Sandstone representing the progradational highstand part of the cycle. The type section of the Newmarracarra Limestone is on Round Hill, at MGA 286550E 6816950N, 300 m south of the disused siding of Grant on the Geraldton–Mullewa line, 3.5 km to the west-southwest of the Bringo cutting.

The Upper Jurassic Yarragadee Formation conformably overlies the Champion Bay Group. The northeastern end of the cutting shows a small anticline with a crestal graben in the Yarragadee Formation (Fig. 33). The cutting is a reference section for the formation (Playford, Willmott and McKellar in McWhae et al., 1958), even though less than 16 m is exposed compared to almost 3000 m in the Gingin wells (Backhouse, 1984, 1988).

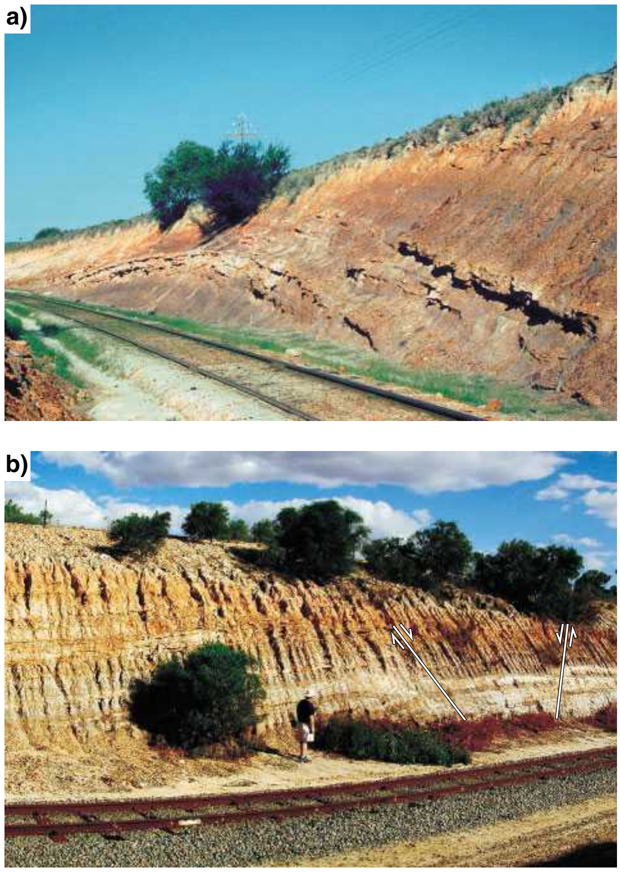

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Figure 33. Small anticline in Yarragadee Formation, Bringo cutting: a) view of western bank taken in 1952 by P. E. Playford; b) view of eastern bank showing small faults taken in 1997 (MGA 290100E 6818760N)

Locality 17: Cape Burney, Greenough

Summary: Good coastal exposure of coral reef and eolian facies in the Pleistocene Tamala Limestone.

Location: About 11 km south of Geraldton, MGA 269330E 6804160N, GERALDTON.

Access: If travelling in a four-wheel drive vehicle, cross the sandbar in the Greenough River, proceed to the car park just south of the river mouth, and walk south 100 to 400 m along low cliffs and beach. Otherwise park next to the public toilets on the north side of the river and walk 900 m. Do not attempt to drive across if the sand bank is under water or the river is flowing. The site is on vacant crown land so permission for access is not needed.

Geology: The locality was first mentioned by Fairbridge (1950) and contains coral reefal facies (Fig. 34) similar to exposures at Leander Point (Locality 30 near Dongara) and on Rottnest Island (Teichert, 1950; Playford, 1988). The most recent dating by Stirling et al. (1998) yielded U-series ages of 121.7 to 123.5 ± 0.5 ka from corals in growth positions. The following summary of this location is Johnson et al.'s (1995) abstract*:

> 'A low, rocky shoreline and attached abrasion platform of Late Pleistocene age are marked by a sharp disconformity within the Tamala Limestone Formation at Cape Burney. Colonization by an intertidal to shallow subtidal biota dominated by encrusting coralline red algae, oysters, and tube-dwelling worms occurs on a sandstone surface with a channelled topographic relief of 20–30 cm. The ancient rocky shore above this level retains trace fossils characteristic of a boring barnacle, probably belonging to *Lithotrya*. The Cape Burney Sandstone Member within the Tamala Limestone is a distinctive unit on which the disconformity sits. Shell beds with a diversity of 35 species, dominated in volume by robust gastropods such as *Turbo intercostalis* and *T. torquatus*, thinly drape portions of the disconformity surface. Succeeding the shell drapes is a reef limestone with a maximum thickness of more than 2 m. The limestone is a massive accumulation of collapsed but otherwise mostly undisturbed coral fronds belonging primarily to a robust species of *Acropora* named the Bootenall Limestone Member of the Tamala Limestone. Based on an analysis of electron spin resonance from *Acropora* samples, the fringing reef developed between 120 ka and 132 ka, in the terminal stage of coastal transgression during the last interglacial period (Oxygen Isotope Substage 5e).'

* Reprinted from 'Colonization and reef growth on a Late Pleistocene rocky shore and abrasion platform in Western Australia', by Johnson et al. (1995) from Lethaia (v. 28, p. 85–98; www.tandf.no/leth) by permission of Taylor & Francis AS.


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Figure 34. Corals in Tamala Limestone, Cape Burney (MGA 269330E 6804160N)

Locality 18: Coaramooly Pool, Greenough River

Summary: Moderate cliff exposure of fluvial pebbly sandstone and carbonaceous siltstone facies of the Upper Permian Wagina Sandstone.

Location: About 4.5 km northeast of Eradu, MGA 311285E 6828020N, INDARRA.

Access: Drive about 17.7 km southwest on the Old Geraldton Road and Eradu Road North from the junction with Peters Road, or 5.2 km northeast on Eradu Road North from the rail crossing at Eradu, to a farm gate at MGA 311530E 6826700N. Drive 600 m north along the fence and through the next gate. Then either drive along the edge of the paddock (soft sand), or part way along the farm track and across the paddock, to the northeastern corner of the paddock. Climb down the bank and walk 100 m upstream. Contact L. & S. Cream ('Riverina Park' Eradu North Rd, Eradu 6532, ph. 08 9924 4046) for access.

Geology: The Upper Permian Wagina Sandstone is exposed in a cliff section on the south bank of the Greenough River. The unit consists of white, cross-bedded pebbly clayey sandstone (Fig. 35) with a thin bed of carbonaceous shale at the base of the cliff that was excavated early last century as a possible coal seam. The predominance of planar and trough cross-beds in the pebbly sandstone and conglomerate, and lack of fine-grained interbeds apart from the carbonaceous shale bed, indicates a high-energy environment. V-shaped profiles lined with pebbles preserved near the base of the cliff have the appearance of small ice wedges, but are more likely to represent contorted strata because Late Permian palaeotemperatures in the Canning Basin were temperate (Archbold and Shi, 1995). Palaeocurrent data from this and nearby outcrops along the river are predominantly to the south, whereas mostly northerly directions have been recorded from outcrop east of Mingenew next to the Darling Fault. In general, the coarse-grained facies resemble those from the Dongara Sandstone, but without the bioturbation, implying the unit is a fluvial deposit. The Late Permian age of the outcrop is indicated by

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Figure 35. Wagina Sandstone at Coaramooly Pool, Greenough River (MGA 311285E 6828020N)

palynolomorphs from nearby Western Mining and Griffin coal exploration bores (Denman and O'Neil, 1981; Meyer, 1985), and Abbewardo 1, 12 km to the northeast (about 150 m south of the junction of Old Geraldton Road with Eradu Road North).

Locality 19: Ellendale Pool, Greenough River

Summary: Difficult-to-access cliff of fluvial Lower Jurassic Chapman Group and shallow marine Champion Bay Group, cut by a small fault.

Location: About 36 km southeast of Geraldton, MGA 302300E 6805700N, GERALDTON.

Access: Off Ellendale Road northeast of Walkaway. The locality can also be accessed from the Geraldton – Mount Magnet Road to the north via Sandsprings Road. The cliff on the south side of the pool is steep and extremely crumbly, so for safety reasons should only be viewed from the north side. The site is on a reserve for which permission for access is not required. Campsites with toilet and barbeque facilities are provided on the north side of the pool.

Geology: Jurassic sedimentary rocks of the Chapman and Champion Bay Groups are exposed in the cliff section (Fig. 36). Most of the 40 m-high cliff comprises pale buff sandstone and shale of the Lower Jurassic Moonyoonooka Sandstone (Chapman Group, an equivalent of the uppermost part of the Cattamarra Coal Measures), which shows a number of stacked, thin upward-fining cycles of likely point bar origin. The overlying massive, pale red-brown sandstone in the top quarter of the cliff is probably the Middle Jurassic Colalura Sandstone of the Champion Bay Group (equivalent to the Cadda Formation). The undulating sharp contact between the Moonyoonooka Sandstone and the overlying Colalura Sandstone is interpreted as a significant disconformity or sequence boundary. The Colalura Sandstone fines upward into an interbedded sandstone and shale interval that is, in turn, overlain by the Bringo Shale, forming the more gentle sloping section. At the top of the cliff the ferruginized Newmarracarra Limestone is especially prominent. A small normal fault is in the centre of the cliff.

Locality 20: Eradu

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

Location: Road cutting about 43 km east of Geraldton, MGA 308730E 6823175N, INDARRA.

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

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Figure 36. Panorama of mid-Jurassic strata showing small fault, Ellandale Pool (MGA 302300E 6805700N)

a)

b)

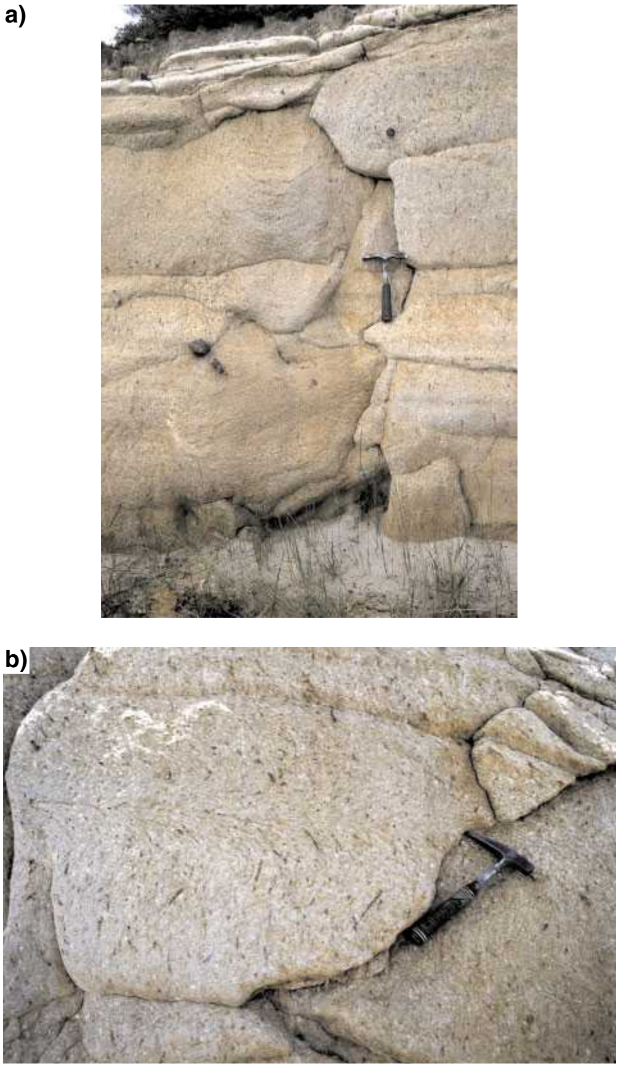

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Figure 37. Road cutting in Yarragadee Formation, Eradu (MGA 308730E 6823175N): a) possible tree cast; b) bioturbation

(Fig. 37a) has been variously interpreted as a cast of a tree root or a giant burrow, but bioturbation near the feature (Fig. 37b) 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).

Locality 21: Moonyoonooka

Summary: Narrow gullies with Lower Triassic Kockatea Shale overlain by fluvial facies of the Lower Jurassic Chapman Group (type sections of the Greenough and Moonyoonooka Sandstones), and patchy exposure of Middle Jurassic Champion Bay Group.

Location: About 20 km east of Geraldton, from MGA 285910E 6814060N to MGA 285050E 6813520N, GERALDTON.

Access: Drive south 2.3 km on Ivan Goulds Road (joins Geraldton – Mount Magnet Road at MGA 284670E 6815980N), turn south onto a farm track, drive 300 m and park near the gully. Walk up the gully. Contact Blakeney Pty Ltd (P.O. Box 3292, Bluff Point 6530) for access.

Geology: Type sections of the Greenough and Moonyoonooka Sandstones, which together comprise the Chapman Group, lie in this narrow gully between the underlying Lower Triassic Kockatea Shale and overlying Colalura Sandstone and Newmarracarra Limestone of the Champion Bay Group (Fig. 38; Playford, P. E., 1959). All units are essentially flat lying. In this section the Kockatea Shale is less than 10 m thick and is best exposed in the small dam next to the farm track. The contact with the 19 m-thick Greenough Sandstone is covered whereas the next contact with the 25 m-thick Moonyoonooka Sandstone is well exposed where the gully steepens abruptly. The Greenough Sandstone is poorly sorted, argillaceous, mostly massive and strongly mottled compared to the predominantly yellow, fine-grained, well-bedded, feldspathic Moonyoonooka Sandstone, which also contains minor carbonaceous siltstone. The overlying ferruginous, wood-bearing Colalura Sandstone is best exposed in the bare hillside just east of the gully, whereas the Newmarracarra Limestone is exposed slightly higher on the west side of the gully. The type section of the Colalura Sandstone is on Spion Kop, the prominent breakaway north of the farm track at MGA 286300E 6814600N, 400 m north of Ivan Goulds Road.

Locality 22: Sheehan Hill, Glengarry

Summary: Good exposure of the contact between Mesoproterozoic Northampton Complex and Lower Triassic Kockatea Shale.

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Figure 38. General view of mid-Jurassic Moonyoonooka section (photograph taken from MGA 285050E 6813520N)

Location: About 19 km east-southeast of Geraldton, MGA 285000E 6811000N, Geraldton.

Access: Drive 8 km south and east on the Glengarry Road off the Geraldton – Mount Magnet Road and either walk north 1.5 km to the base of Sheehan Hill or drive across the paddock to the easterly-trending gully if your vehicle has sufficient ground clearance. Obtain permission to enter by contacting the manager of Glengarry station (ph. 08 9923 3522) beforehand (the homestead is 2.5 km further east).

Geology: The section consists of flat-lying Triassic and Jurassic strata unconformably overlying gneiss of the Northampton Complex (Fig. 39). The Triassic Kockatea Shale contains a 25 cm-thick basal conglomerate and pebbly sandstone, and is in turn overlain by the Jurassic Greenough Sandstone. The basal coarse-grained bed is here considered to be part of the Kockatea Shale, at a higher stratigraphic level than the lowermost Triassic Bookara Sandstone Member. The only fossils known from the Kockatea Shale in the immediate area are microscopic gastropods and bivalves recovered from the clay quarry 2.2 km south-southwest of Sheehan Hill. The upper part of the hill contains Lower Jurassic sandstone facies of the Chapman Group.

Figure 39. Unconformity between basement and Triassic Kockatea Shale, Sheehan Hill (MGA 285000E 6811000N)

Locality 23: Urch Road, Chapman Valley

Summary: Low road cutting showing erosional contact between fluvial facies of the Lower Jurassic Moonyoonooka Sandstone and shallow-marine facies of the Middle Jurassic Champion Bay Group.

Location: Road cutting about 20 km northeast of Geraldton, MGA 280240E 6830250N, Geraldton.

Access: About 4 km east along Urch Road from the Chapman Valley Road. Note that there is little room to park safely close to this exposure.

Figure 40. Champion Bay Group cutting into Moonyoonooka Sandstone, Urch Road, Chapman Valley (MGA 280240E 6830250N)

Geology: This road cutting (Fig. 40) exposes the contact between the Moonyoonooka Sandstone of the Chapman Group (equivalent to the Cattamarra Coal Measures) and the overlying Champion Bay Group (equivalent to the Cadda Formation). The Moonyoonooka Sandstone is thinly bedded with ripple cross laminations and is interpreted as stacked middle to upper point-bar cycles, whereas the overlying Colalura Sandstone is massive, very coarse to medium grained with minor conglomeratic bands, plant impressions, fossil wood and rare bivalves, from which a nearshore origin is interpreted. Minor oval-shaped phosphate-rich ferruginous nodules around 2 cm long are also present. The undulating contact shows up to 1.5 m of erosion in the cutting, and is considered to be a significant sequence boundary.

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 24), at the junction of the north and south branches of the

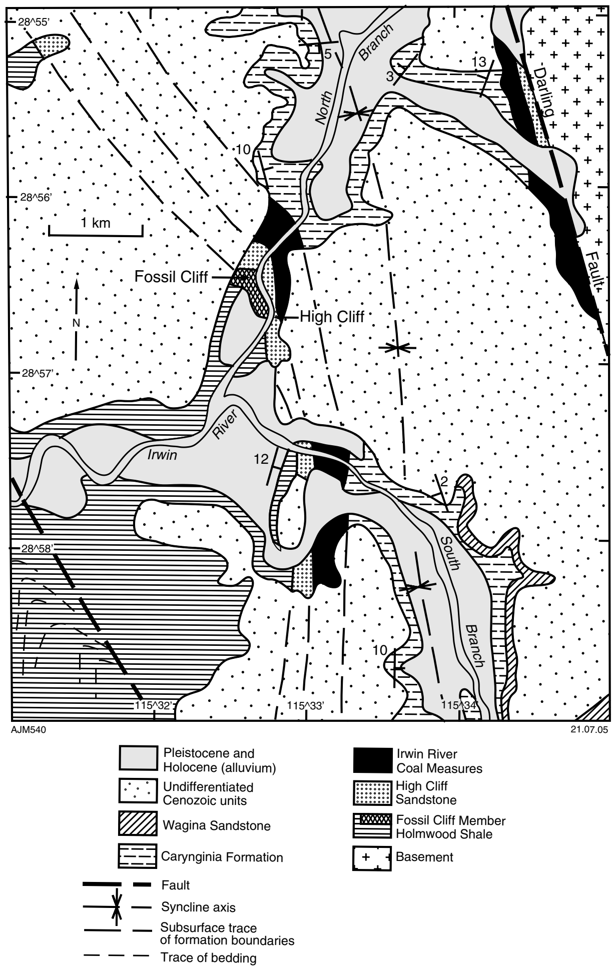


Figure 41. Simplified geological map of the junction of the North and South Branches of the Irwin River (after Clarke et al., 1951; Le Blanc Smith and Mory, 1995)

Irwin River (Figs 41–46), 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 glacigene 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 Mingenew Formation appear to be laterally equivalent to the lower part of the Carynginia Formation but are known only from a few outcrops near Mingenew.

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 Asselian–Sakmarian palynomorphs. Mid- to Late Carboniferous palymorphs 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’ at 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.

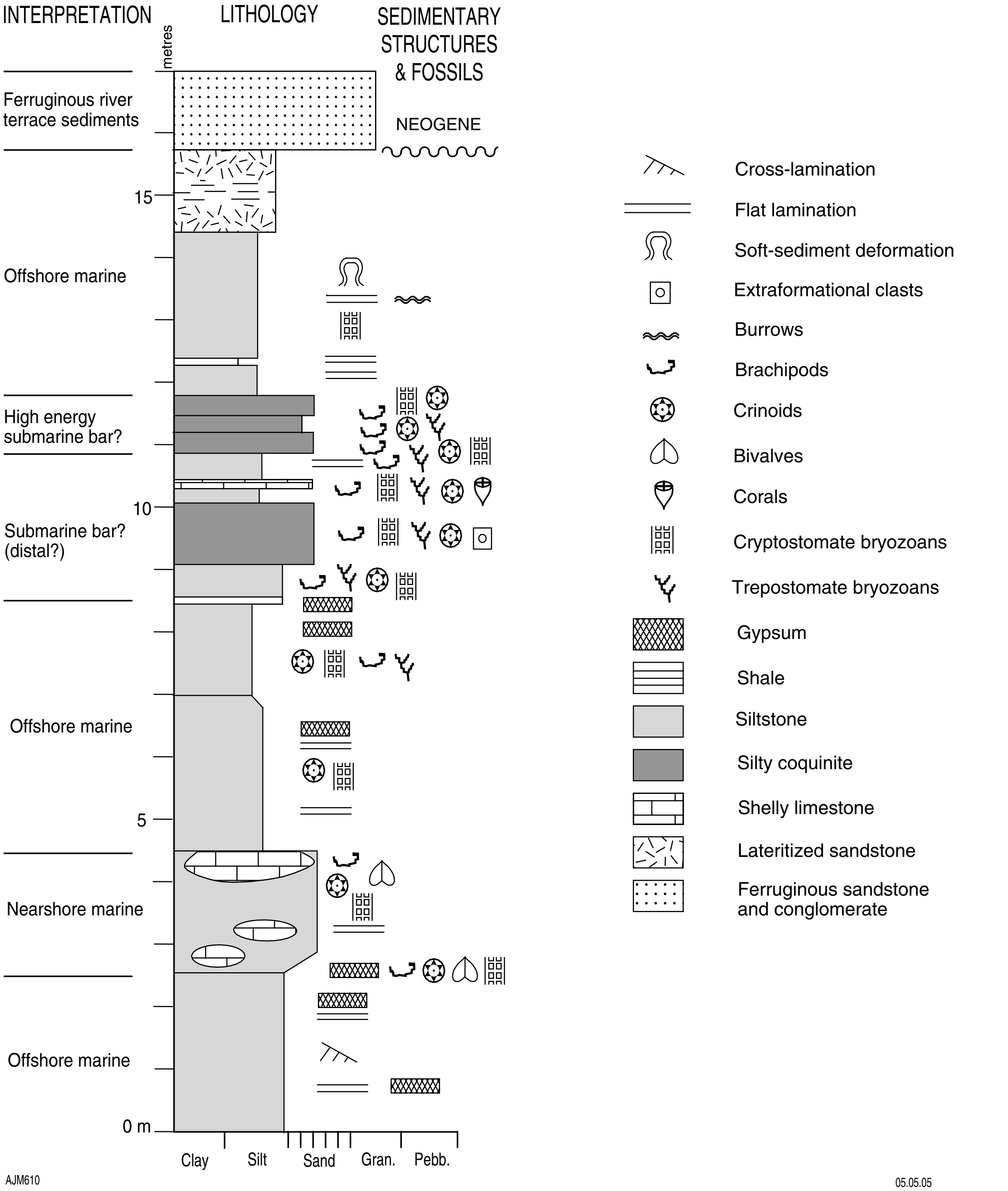


Figure 42. Measured section, Fossil Cliff, Irwin River (MGA 357785E 6789390N). After McLoughlin in Haig et al. (1991)

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. 42). 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. 43) 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 (*Planolite*s- and *Rosselia*-type) burrow forms are abundant (Fig. 47a). 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. 47b) 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. 47c) 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. 47c,d). Although previously regarded as fluvial (McIntosh, 1980), the unit is here interpreted to represent various delta plain depositional environments (Fig. 43). 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. 44). The unit contains an abundant, but typically low diversity, Early Permian Gondwanan flora incorporating species of *Glossopteris*, *Vertebraria*, *Gangamopteris*, *Sphenophyllum*, *Neomariopteris*, *Paracalamites*, *Lelstotheca*, and *Gondwanophyton* (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 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 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. 47e). 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 45 and 47f). 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 24: 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; 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.

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 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. 42). 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.

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 43 and 47a). The predominantly

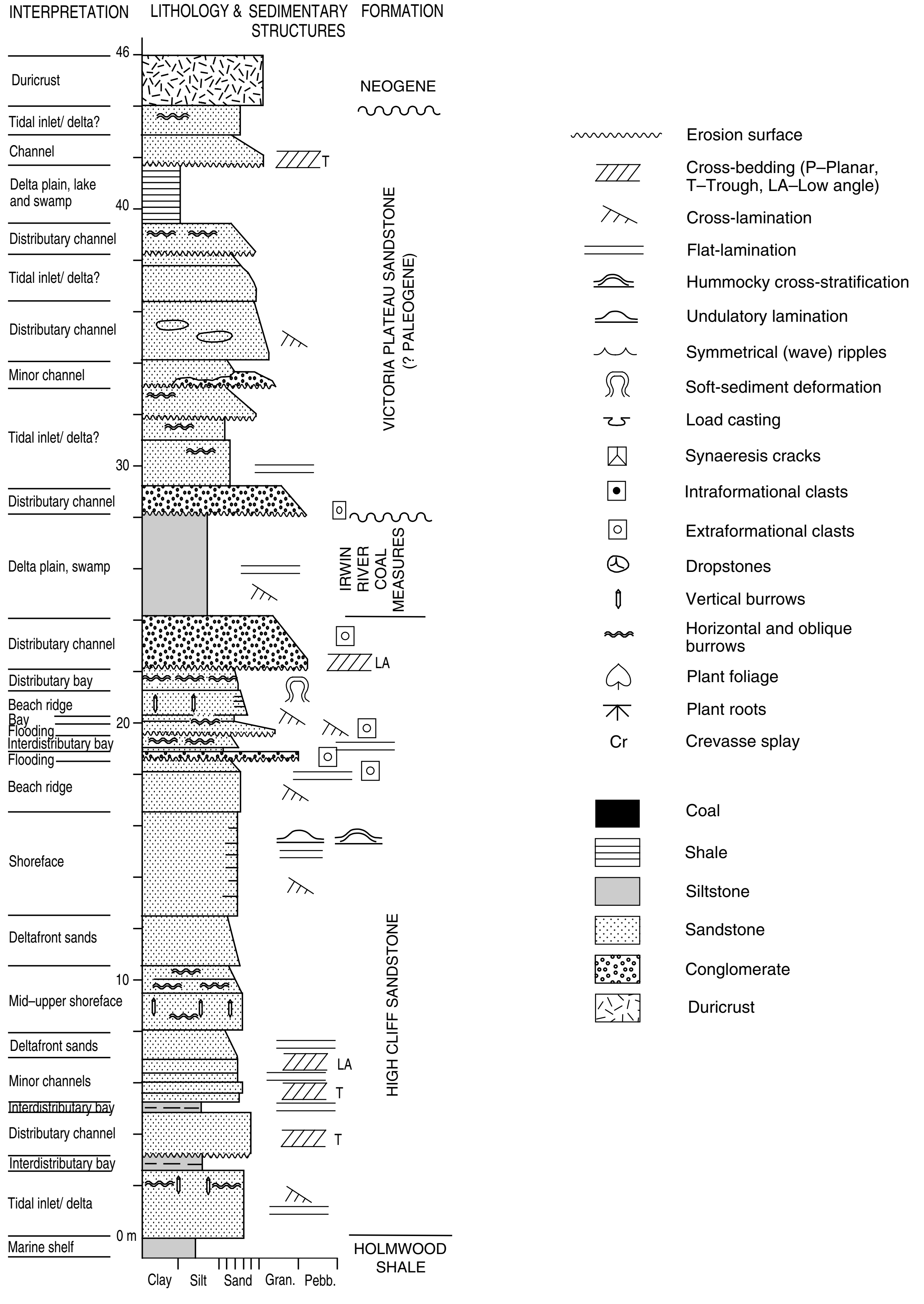


Figure 43. Measured section, High Cliff, Irwin River (MGA 358580E 6797235N). Modified after McLoughlin in Haig et al. (1991)

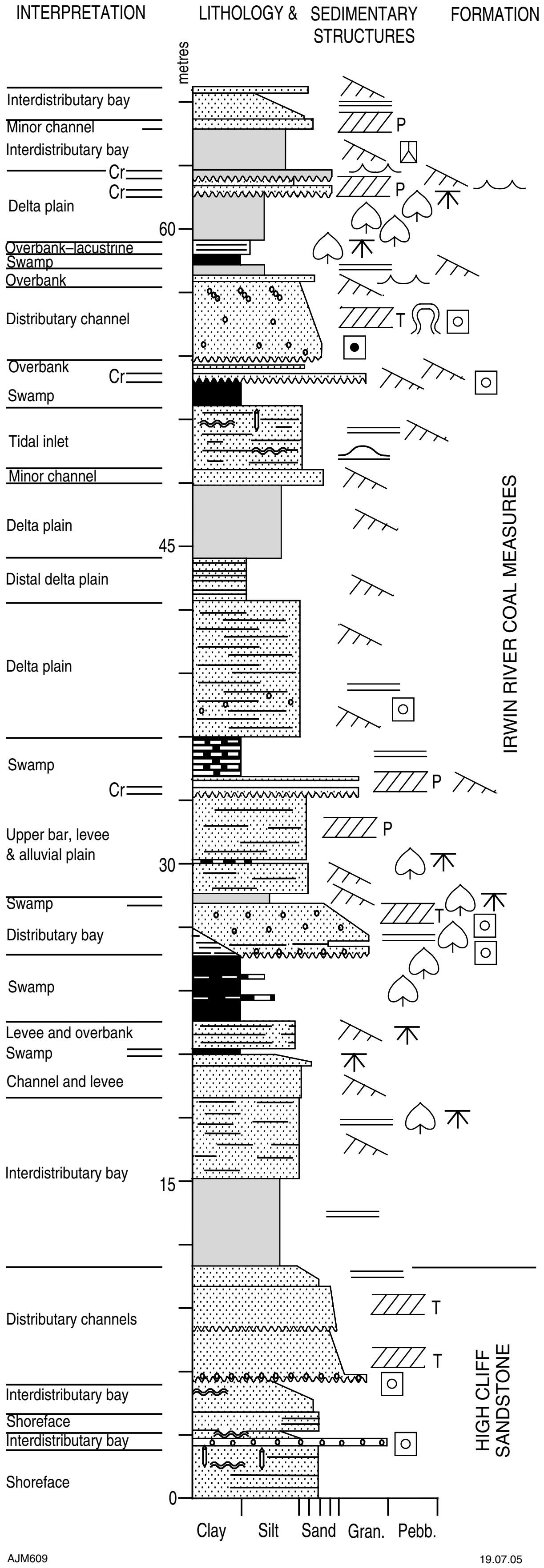
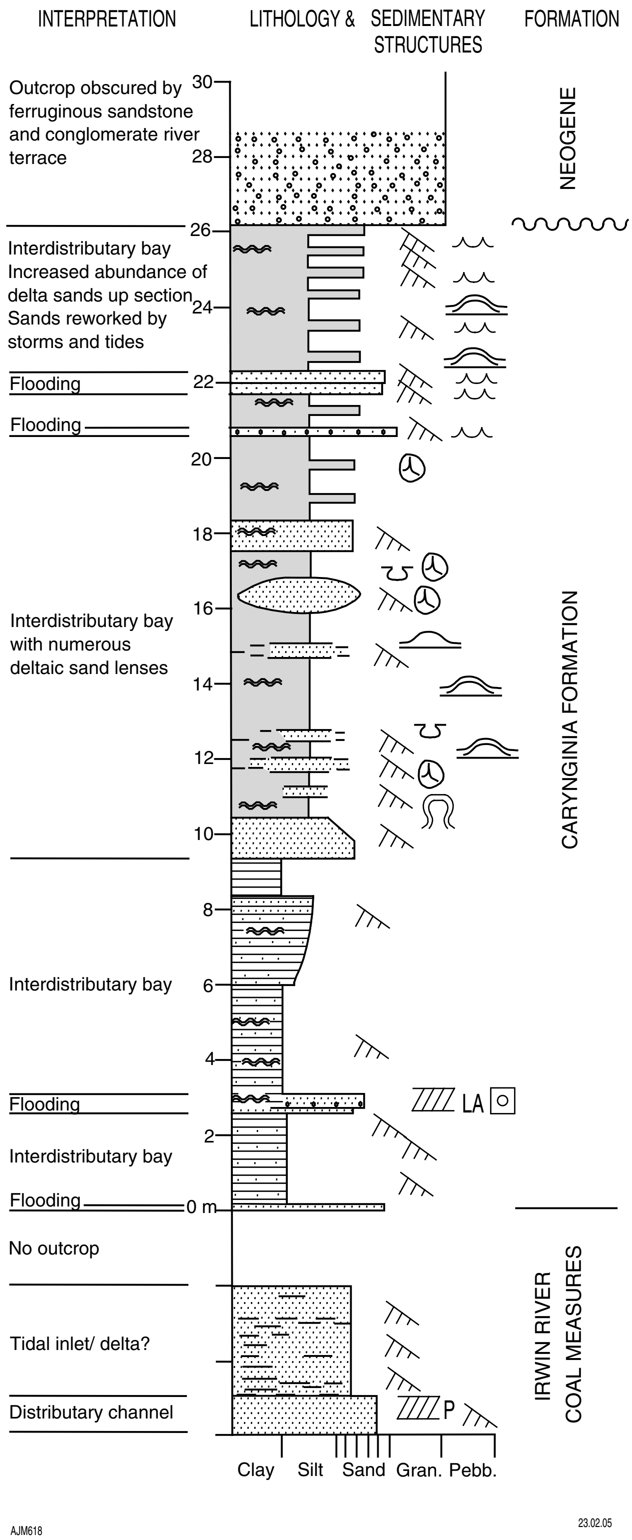


Figure 44. (left) Measured section, North Branch, Irwin River. Section extends from MGA 358450E 6797850N to 358810E 6798120N. See Figure 43 for reference. After McLoughlin in Haig et al. (1991)

Figure 45. (below) Measured section, South Branch, Irwin River (MGA 359290E 6795715N). See Figure 43 for reference. After McLoughlin in Haig et al. (1991)



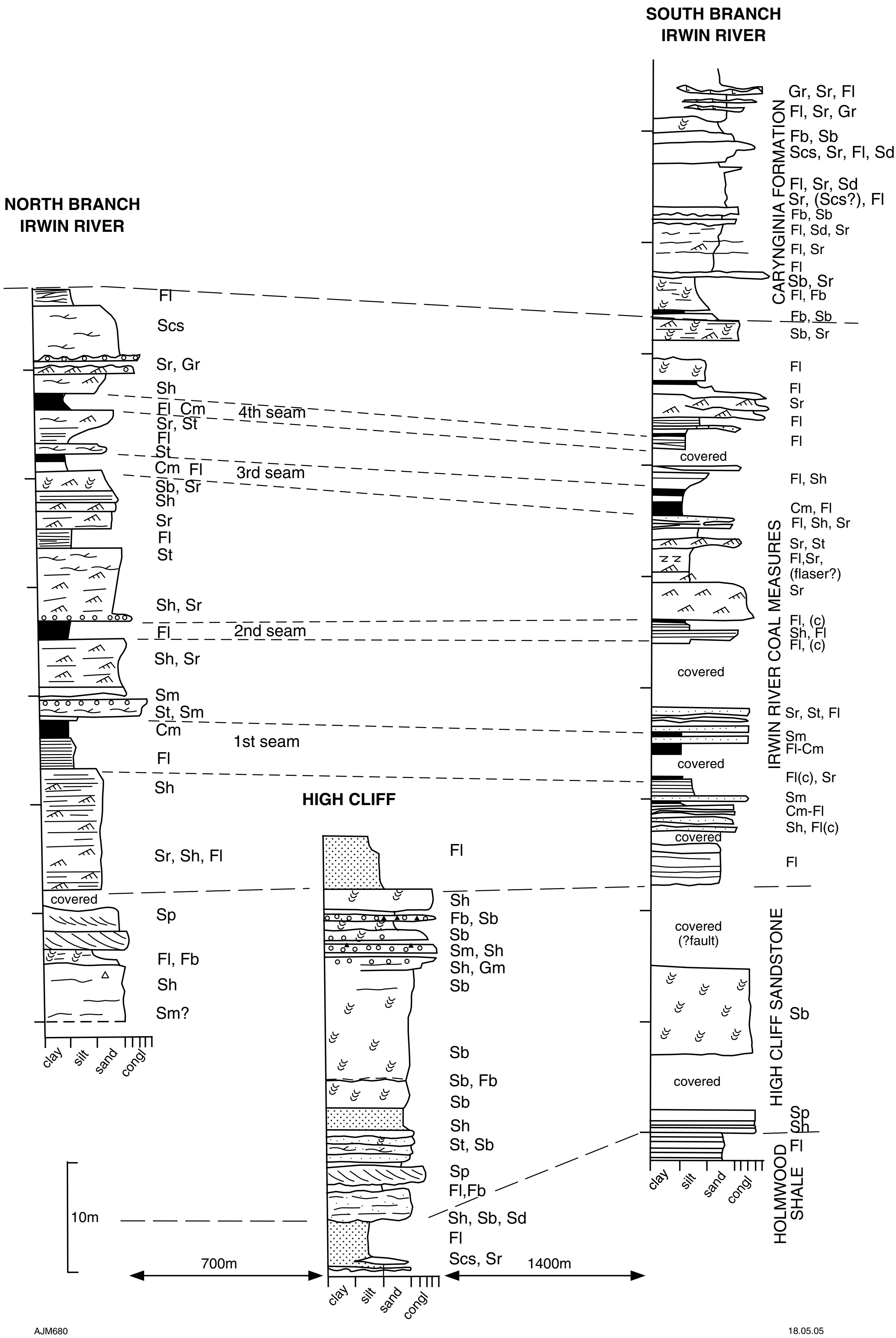


Figure 46. Correlation of Lower Permian sections at High Cliff, and North and South Branches, Irwin River. Modified from Eyles et al. (in prep.). See Figure 27 for code to facies

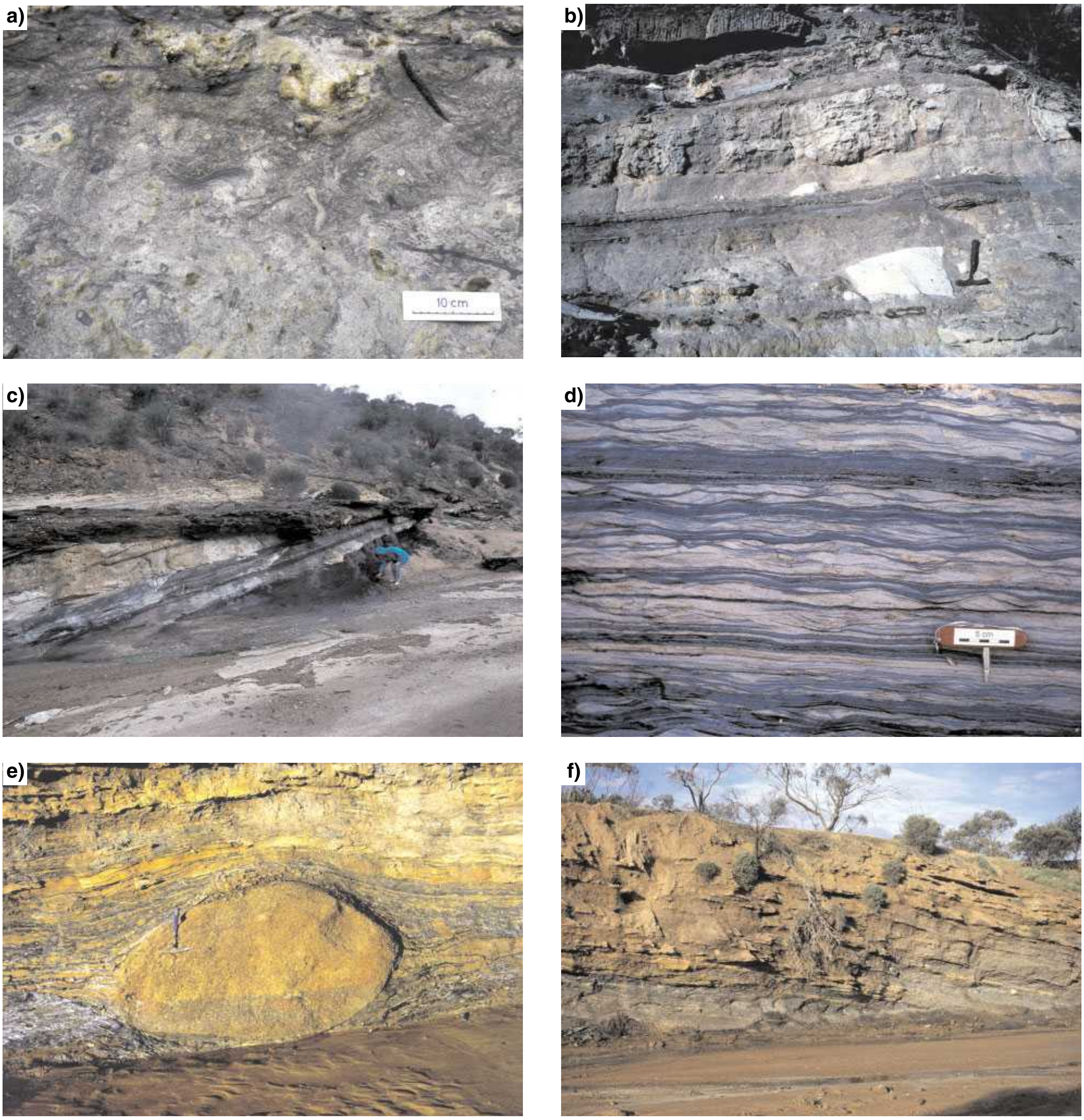


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Figure 47. Lower Permian outcrops on the Irwin River: a) bioturbation in the High Cliff Sandstone; b) granite dropstone, High Cliff Sandstone; c) adit in coal, Irwin River Coal Measures; d) wave ripples, Irwin River Coal Measures; e) large dropstone, Carynginia Formation; f) lower Carynginia Formation; a–b) High Cliff (MGA 358580E 6797235N), c) North Branch (MGA 358600E 6798100N), d–f) South Branch (d) MGA 358700E 6795830N; e) MGA 358950E 6795800N; f) MGA 358870E 6795830N

carbonaceous and highly bioturbated sandstone beds contain large angular to subangular granite, quartzite and chert erratics, up to 60 cm across (Fig. 47b). 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. 48).

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

Figure 48. High Cliff showing the unconformable contact between the Lower Permian and Cenozoic units. Panorama compressed 50% horizontally

High Cliff and Fossil Cliff, and contains four low-rank coal seams interbedded with coarse- to fine-grained sandstone, siltstone, and claystone (Figs 44 and 47f). 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 45 and 47f). 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. 47e) 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 25: Woolaga Creek

Summary: Patchy exposures along creek and hills to east of Lower Permian Holmwood Shale, High Cliff Sandstone, Irwin River Coal Measures, and Carynginia Formation (reference section), and fluvial facies of the Upper Permian Wagina Sandstone (reference section).

Location: About 21 km east of Mingenew, from MGA 369290 E 6769940N (High Cliff Sandstone) to MGA 370050E 6770420N (Carynginia Formation), YANDANOOKA.

Access: Turn into 'Woolaga' about 1.1 km south of the Mingenew–Moorowa Road on Yandanooka Northeast Road, drive between sheds and then southeast around paddock on south side of the fence. Drive around the hill to the edge of Woolaga Creek at MGA 369170E 679920N, and walk upstream. A four-wheel drive vehicle may be necessary past the sheds. It is inadvisable to drive past the sheds when the ground is wet. Alternatively, it may be possible to drive 1.8 km south from the Mingenew–Moorowa Road to the east end of the exposures via the west side of the sandstone ridge immediately south of the entrance to 'Ebano'. Contact Ian and Murray Thomas (P.O. Box 39, Mingenew, 6522, ph. 08 9928 1122 or 08 9928 1157) for access via 'Woolaga', and Geoff Yewers ('Merkanooka' P.O. Box 232, Morowa, 6623, ph. 08 9971 6035) to access the main outcrops along Woolaga Creek.

Geology: The best exposures of the Lower Permian are along the creek and its tributaries between MGA 369290E 6769940N and MGA 370050E 6770420N, and were first described by G. Playford (1959). This is the only section south of the Irwin River that shows most of the Lower Permian units although the exposures are not as continuous as at Coalseam Conservation Park and are complicated by small faults.

Most of the outcrop of High Cliff Sandstone is either deeply weathered or ferruginized, shows little lateral continuity and virtually no bedding, so it is difficult to distinguish different levels. The formation here is

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Figure 49. Lower Permian outcrops at Woolaga Creek: a) internal moulds of *Neospirifer (Quadrospira) woolagensis* in High Cliff Sandstone (MGA 369290E 6769940N); b) sandstone boulders in High Cliff Sandstone (MGA 369575E 6769985N); c) hummocky cross stratification in Caryngினia Formation (MGA 369865E 6770530N); and d) onlap surface in Caryngினia Formation (near foot of person; MGA 370050E 6770420N)

fossiliferous (Fig. 49a), unlike the type section. Most of the fossils come from the low ridge immediately south of the creek above poorly exposed Holmwood Shale (MGA 369290E 6769940N), but it is rare to find fossils without hammering the surface and thereby destroying either the internal or external moulds. The tributary to Woolaga Creek immediately east of the fossil location has better exposures of the unit with a few small sandstone boulders (Fig. 49b), but is unfossiliferous.

The Irwin River Coal Measures were measured as 123 m thick in Woolaga Creek (Playford, G., 1959), but Le Blanc Smith and Mory (1995) reported 76 m from an exploration drillhole adjacent to the creek. The discrepancy is probably due to G. Playford (1959) including a sand-rich section of the Caryngினia Formation in his measured section. Notable features in this section include hummocky cross stratification (Fig. 49c) above a thin coal seam, and minor onlap surfaces (Fig. 49d).

The 250 m-thick reference section for the Wagina Sandstone extends east from Red Hill (MGA 370840E 6770850N) to the centre of a small syncline (MGA 370850E 6771750N) close to the Darling Fault. The section contains mostly fine- to medium-grained sandstone with minor siltstone, conglomerate and a coaly bed. The thickness was estimated mostly from dips on aerial photographs by G. Playford (1959) and has been dated from a shallow bore (UWA 4) near the top of the exposure (Balme, 1964; Backhouse, 1993). A more accessible exposure is in the gully east of Ebano farmhouse just north of the Mingenew–Morowa road.

Locality 26: Irwin River, north of Depot Hill

Summary: Long riverbank exposure showing channel avulsion in partly bioturbated fluvial facies of the Upper Jurassic Yarragadee Formation.

Location: About 11 km west-northwest of Mingenew, from MGA 339820E 6776110N to MGA 339700E 6776030N, MINGENEW.

Access: Although the site is on a Shire of Mingenew reserve the most direct access is via an unoccupied farmlet. Contact T. Obst (39 Petchell St, Rangeway, 6530, ph. 08 9921 8496) for access. Drive 600 m east of the junction of Strawberry Northeast Road with Depot Hill Road, and a further 600 m northeast across the paddock around the contour bank (not recommended for vehicles with low clearance) north of the shed to a gate (at MGA

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Figure 50. Panoramas showing channel avulsion in Yarragadee Formation, Irwin River (taken in 1991): a) (at MGA 339820E 6776110N) is 100 m upstream from b) (at MGA 339800E 6776010N)

339420E 6775940N). In 2004, thick reeds extended along the river next to the exposure, but it can be reached most easily at its southern end.

Geology: On the east bank of the river is a 5–6 m high and 200 m long exposure of predominantly fine-grained bioturbated sandstone of the Upper Jurassic Yarragadee Formation dipping 2° north. The section is interpreted as an overbank deposit in which the unusual dips are due to lateral migration of small dunes and channel avulsion (Fig. 50). The channels appear to have flowed northwards, similar to palaeocurrent directions from the coarse sandstone above the riverbank (Mory, 1995b, fig. 10, locality 272). Small-scale structures such as bioturbation (Fig. 51), ripples, cross-beds, and slumps are visible where loose clay and sand on the surface has been washed off the outcrop.

Locality 27: 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, MGA 338000E 6774250N, MINGENEW.

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 (at 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. 52a). Large cross-beds in coarse pebbly sandstone at the base of the cycle indicate a westward palaeocurrent flow (Fig. 52b; Mory, 1995b, fig. 10, locality 424). The cross-beds appear to become progressively smaller

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Figure 51. Bioturbation in rippled fine-grained sandstone, Yarragadee Formation, Irwin River (MGA 339800E 6776010N)

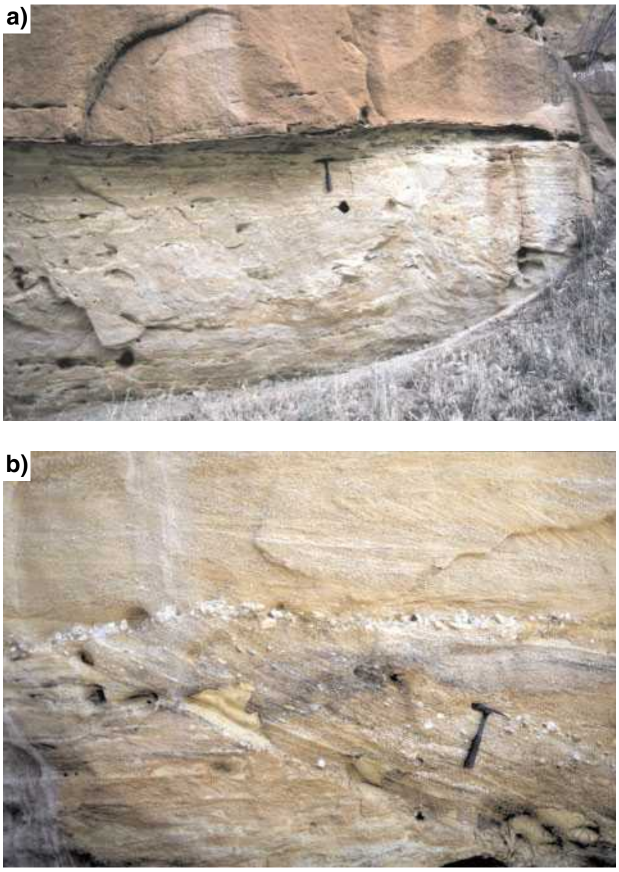

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Figure 52. Fining-up cycle in Yarragadee Formation, Irwin River: a) lower contact with contorted beds; b) cross-bedding in lower part of cycle (MGA 338000E 6774250N)

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.

Locality 28: Mingenew–Mullewa Road

Summary: Low road cutting showing slumping in fluvial facies of the Upper Jurassic Yarragadee Formation.

Location: Road cutting approximately 4 m high and 70 m long, about 4.5 km due north of Mingenew, MGA 348460E 6774680N, MINGENEW.

Access: Drive 4.5 km due north of Mingenew on Mingenew–Mullewa Road. Park away from the cutting where the road is wider.

Geology: The cutting in the Upper Jurassic Yarragadee Formation shows slumping in thinly bedded medium- to fine-grained sandstone and siltstone in the lower half, overlain by flat-lying sandstone beds (Fig. 53). In the lower half of the outcrop, medium-grained sandstone

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Figure 53. Slumping in Yarragadee Formation, road cutting on Mingenew–Mullewa Road (MGA 348460E 6774680N). Hammer (circled) for scale

typically forms large pillows surrounded by finer grained beds into which small low-angle faults detach. The faults do not appear to extend into the upper part of the outcrop. The slump is probably due to rapid deposition of water-saturated sediments, which collapsed under the weight of additional sediment before much dewatering took place.

Locality 29: Yarragadee

Summary: Low ridge showing fluvial facies of the Upper Jurassic Yarragadee Formation (type section; Fig. 54) close to the Urella Fault.

Location: About 11 km north-northwest of Mingenew, from MGA 346265E 6780320N to MGA 345950E 6780470N, MINGENEW.

Access: Drive 500 m west across paddock to low hill from Mingenew–Mullewa Road, via the gates 1.2 and 1.9 km

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Figure 54. General view of Yarragadee Formation type section (MGA 345950E 6780470N)

south of Scroops Road. Contact M. Pearse (Mullewa Rd, Mingenew, 6522, ph. 08 9928 1130) for access.

Geology: Fairbridge (1953) named these Upper Jurassic outcrops after Yarragadee Station, which is why Playford et al. (in McWhae et al., 1958, p. 98) nominated this hill as the type section of the Yarragadee Formation, even though they conceded that the section is 'a poor one'. Steep dips at the southern end of this ridge (MGA 346415E 6779870N to MGA 346400E 6780050N) are presumably related to the Urella Fault. Nevertheless, dips in the northern part of the hill are less than 10° to the northwest, and a section of cross-bedded fine- to very coarse grained sandstone, pebbly sandstone, and minor siltstone approximately 20–25 m thick is exposed (Fig. 54). Neither upper nor lower contacts are evident, which also explains why Playford et al. (in McWhae et al., 1958, p. 98) nominated reference sections in Bringo cutting (Locality 16) near Geraldton and at Cantabilling Spring in the Hill River area even though the latter is no better exposed than the type section.

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, 1995b).

Locality 30: 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, 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. 55). The reef consists of bafflestone (Fig. 56a) of branching *Acropora* in a shelly calcarenite–calcirudite matrix, and of bindstone (Fig. 56b) 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 *Lithothamion* 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,

Figure 55. Sea cliff in Pleistocene coral reef, Leander Point (MGA 297550E 6759280N)

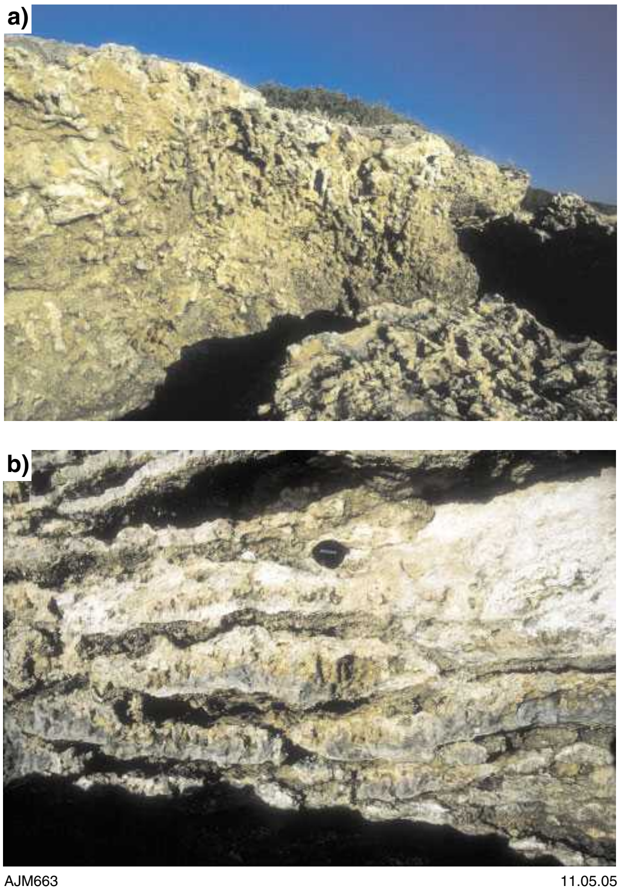

Figure 56. Pleistocene coral facies, Leander Point (MGA 297550E 6759280N): a) bafflestone formed of branching *Acropora*; b) bindstone formed of palmate *Acropora*

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 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.

Cervantes–Jurien area

Background geology

The Cervantes–Jurien area contains a Lower Permian to Upper Jurassic succession, of which only the Upper Triassic to Upper Jurassic is exposed, in a faulted broad anticline feature overlain by thin Cenozoic deposits (Mory, 1994a; Iasky and Mory, 1996). Exposures in the elevated central part of the area, east of the Gingin Scarp, lie mostly within the thickly vegetated Mount Lesueur National Park, into which vehicular access is restricted.

The most prominent geographical feature of the area is the Gingin Scarp along which heavy mineral sand deposits accumulated, presumably in the mid-Neogene, as a series of strandline and dune deposits between 30 and 170 m above present sea level. These deposits are mined at Cataby and Eneabba for ilmenite, rutile, and zircon with minor monazite and leucoxene. In 2003–04, production from these mines was valued at $508 million.

Locality 31: Jurien heavy mineral sand deposit

Summary: Excellent exposures of small faults in eolian facies of the Pleistocene Tamala Limestone, overlying ?Pliocene heavy mineral sand deposit.

Location: About 20 km north-northeast of Cervantes at MGA 325305E 6641880N, HILL RIVER.

Access: Permission to enter the site should be obtained from the Tiwest operations manager at Cooljarloo (08 9690 9200) well beforehand. The site is accessible by two-wheel drive vehicles from the Brand Highway via the Cervantes turnoff (Bibby Road). Then turn right into Munbinea Road and drive 15 km north to Cain Road (5 km north of the next turnoff to Cervantes). Proceed a further 2.5 km west, and walk 500 m north to the workings. Note that Tiwest requires a hardhat, safety glasses and safety boots be worn on this site.

Geology: The mine was excavated for the heavy mineral sands at 36–43 m above present sea level (exposed at the north end of the pit) below the Tamala Limestone (exposed in the walls). The limestone is the cause of much of the poor-quality seismic data along the coast in the Perth Basin. This locality clearly demonstrates post-Pliocene faults in foresets of the Tamala Limestone that are up to 14 m high and are clearly eolian in origin (Fig. 57a,b). There is a small exposure of festoon cross-bedded sandstone (?Upper Triassic Lesueur Sandstone) on the floor of the pit, and some of the heavy mineral sands deposit remains just below the Tamala Limestone at the northern end of the pit.

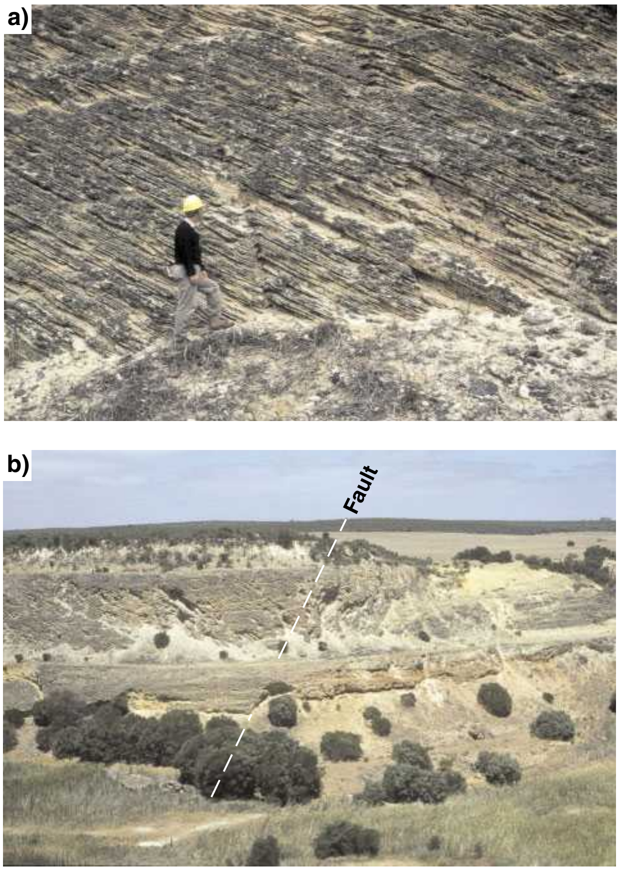

Figure 57. Tamala Limestone, Jurien heavy mineral sand deposit: a) Small reverse faults in eolian foresets (MGA 325095E 6641880N); b) possible strike-slip fault (photographed from MGA 325305E 6641710N)

On the western wall of the mine a number of small reverse faults, each with displacements of about 5 to 10 cm, dip at approximately 80° towards 340° (Fig. 57a). Approximately 200 m to the south of the reverse faults a near-vertical fault, striking at approximately 290°, is implied from two large foresets, each approximately 5 m high, dipping towards each other (Fig. 57b). As the vertical displacement of the later fault is less than 2 m, based on the displacement shown below the bench, some strike-slip movement is necessary to juxtapose the foresets in this manner. If this fault was a product of the same stress field that produced the small reverse movements, a dextral sense of movement is implied. The small reverse faults indicate compression in a north-northwesterly direction, and may be related to a late movement of the Australian plate along the Banda arc. The dextral strike-slip fault may represent a reactivated deeper late-stage strike-slip fault, synthetic to the 310° trend of breakup age evident on images of magnetic data in the region.

At the southern end of the mine there are a few limestone pinnacles up to 3 m high immediately below surficial unconsolidated sand. They presumably formed in a similar manner to those in Nambung National Park, described in Locality 33.

During 1975–1979 Western Mining Corporation Mineral Sands produced 17 167 t of rutile concentrate and 5239 t of zircon concentrate from the deposit. In 1986–1987, 57 456 t of ilmenite concentrate was produced from tailings trucked to Cable Sand's Bunbury treatment plant. Remaining measured heavy mineral sands resources are 7.55 Mt, which includes 4.472 Mt of ilmenite, 0.407 Mt of rutile, 0.238 Mt of leucoxene, and 0.765 Mt of zircon.

Locality 32: 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 5. As mapped by Grey et al. (1990), the substrate of the lake and adjacent foreshore is zoned in

Table 5. 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

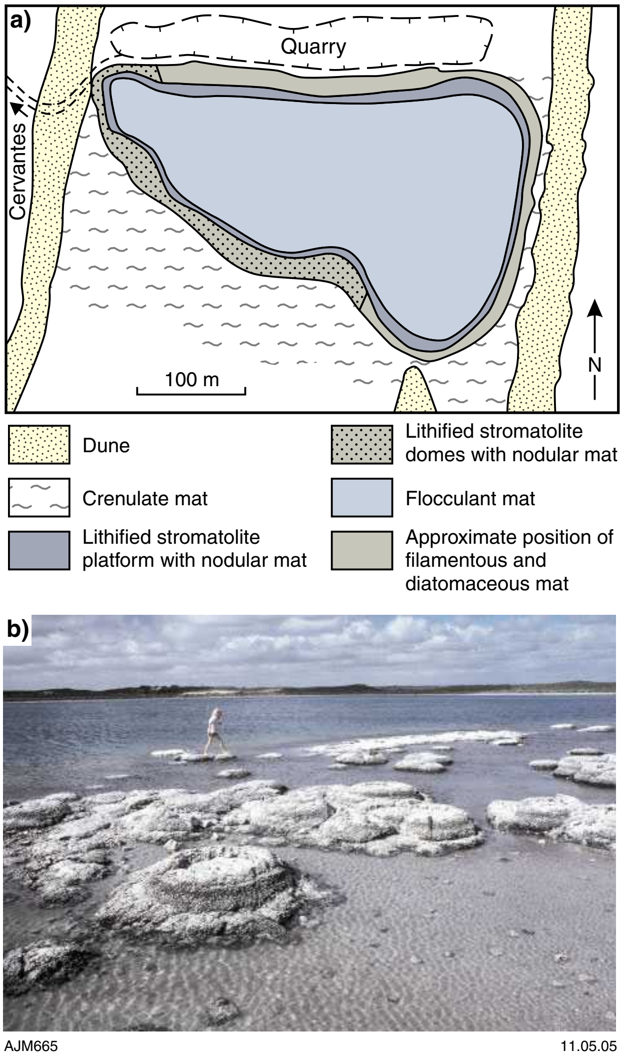

Figure 58. Lake Thetis a) sketch map showing distribution of mat types (after Grey et al., 1990); b) Holocene stromatolites (MGA 315500E 6623400N)

a concentric fashion based on different microbial mat types (Fig. 58a). Five types have been recognized (Table 6), 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. Nodular mat is best seen in the splash zones around the edges of stromatolite domes along the southwestern shoreline (Fig. 58b) 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 flocculent 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 (M. W. Pryce, as cited by Grey et al., 1990). The purple mud of the lake floor includes irregular sandy 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 33: Pinnacles, Nambung National Park

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

Table 6. 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 *Calothrix*, *Scytonem*a, *Gloeocapsa*
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 *Gloeocapsa*
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 *Oscillatoria*
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 *Oscillatoria*, ?*Synechocystis,* ?*Thiocystis* / *Thiocapsa*

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. 59a) commonly exposing abundant calcified fossil rhizoliths (plant roots; Fig. 59b). Some residual sands with fossil soil horizons are present nearby (Fig. 59c). 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, Madagascaran 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 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.

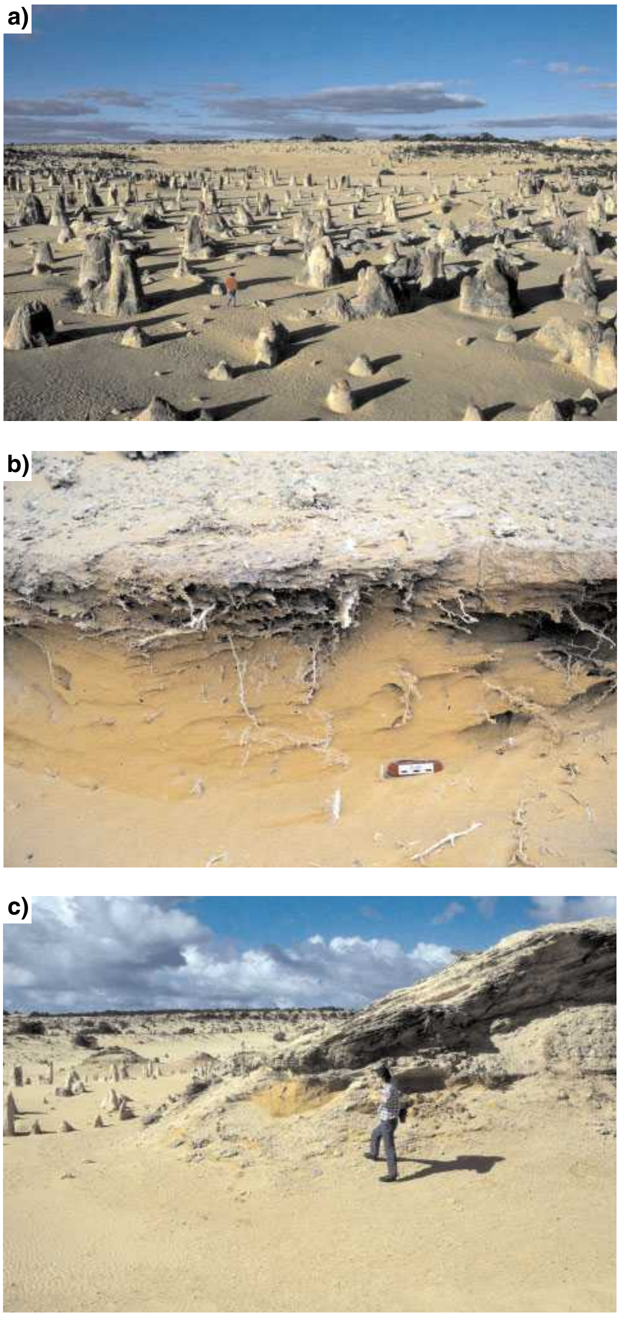

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Figure 59. Tamala Limestone, Pinnacles Desert (MGA 324000E 6613000N): a) general view of pinnacles; b) fossil rhizoliths; c) silica and carbonate sand separated by a fossil soil horizon

Locality 34: Yallalie impact breccia

Summary: Poor road cutting showing breccia with sandstone and greensand clasts on edge of likely impact crater.

Location: About 56 km east of Cervantes; MGA 370900E 6628550N, BADGINGARRA.

Access: Drive 18 km southeast of Badgingarra on North West Road, or 37 km northwest of Moora, to the low road cutting on the north side of the road, 800 m east of the intersection with Mungeda Road. The broad depression over the Yallalie structure is a further 6 km east, near the southern end of Coolara Road.

Geology: The outcrop was mapped as Poison Hill Greensand by Carter and Lipple (1982), and consists entirely of ferruginized sandy breccia containing siltstone clasts from the Upper Jurassic to Lower Cretaceous Yarragadee Formation or Parmelia Group, and Upper Cretaceous greensand. The following account of the structure and breccia is from Bevan et al. (2004)*:

> ‘The Yallalie structure (30°26'40.3"S, 115°46'16.4"E) is a buried circular feature (~12 km in diameter) in Mesozoic sedimentary rocks of the Dandaragan Trough of the Perth Basin, Western Australia (Dentith et al., 1999). The structure is characterised by a central uplift 3–4 km across similar to those in complex impact craters. Quartz grains from the central uplift show the development of prismatic cleavage indicative, though not diagnostic, of low shock levels. However, multiple sets of closely spaced planar deformation features (PDFs) have yet to be observed. Notwithstanding, the morphology of the Yallalie structure suggests an impact origin (Hawke et al., 2003; Hawke, 2003). A polymictic, allochthonous breccia of Jurassic and Cretaceous rocks occurring adjacent to the structure may also be of impact origin (Dentith et al., 1999).
>
> Within Yallalie, there are concentric positive magnetic anomalies centred on a magnetic peak (Hawke, 2003). The anomalies correlate with arcuate faults interpreted from seismic profiles. The magnetic highs are interpreted as marking former terraced interior crater walls. The anomalies appear to post-date impact and may be related to the precipitation of magnetic minerals as the result of hydrothermal alteration. Overall, the unusual signature of Yallalie is similar to impact craters formed in low-strength, volatile-bearing, or water-saturated target rocks, and may indicate subaqueous impact.
>
> The extent of the allochthonous breccia is limited to ~2 km^2 and, although highly variable, its maximum thickness is estimated to be ~30 m. Ridges of breccia occupy a region ~4 km from the southwestern rim of the Yallalie structure. This region preserves a Cretaceous surface (sea bed?) onto which the breccia was deposited. A search for PDFs in quartz from the breccia has so far been unsuccessful. The breccia contains blocks ranging from 2 m in diameter to clasts of a centimetre or less set in a sandy matrix. The matrix of the breccia shows pronounced flow structures around what were more competent clasts, indicating an original mixture of consolidated and semi-consolidated rocks. The bulk of the breccia may have been ejected as fluidised flows. Metre-sized ejecta blocks may have simultaneously fallen back into the deposit, or were also swept by the flow.

* Reprinted from abstracts of the 17th Australian Geological Convention — Dynamic Earth: Past, Present and Future — by permission of the Geological Society of Australia.

Assuming a causal relationship, the allochthonous breccia provides the only evidence of the age of the Yallalie structure. Breccia lithologies recognised so far include siltstones of the Yarragadee Formation (Late Jurassic to Early Cretaceous), and the Molecap Greensand (Cenomanian–Coniacian). Stratigraphy indicates that the age of the breccia, and therefore the impact event, is bracketed between the Gingin Chalk (Santonian) and the Poison Hill Greensand (Campanian).'

Gingin area

Background geology

Cretaceous strata extend along part of the Gingin Scarp and on the Dandaragan Plateau but exposures are poor, even near Gingin where this succession was first mapped (Fig. 60). Most of the outcrops in this area are confined to gullies cut into the scarp, and belong to the Coolyena Group (Table 7). Only the Gingin Chalk contains fossils that allow a direct correlation to the standard chronostratigraphic scale. McNamara et al. (1993) provides a comprehensive set of illustrations of Gingin Chalk macrofossils. The Osborne Formation, Molecap Greensand, and Poison Hill Greensand contain dinocyst and spore–pollen assemblages that allow correlation to local palynomorph zonations outlined by Marshall (1985), but which are also used widely in petroleum exploration on the North West Shelf of Western Australia; and defined more widely by Helby et al. (1987). The units are subhorizontal, although there are differences in thickness over small distances indicating that some of the contacts are irregular.

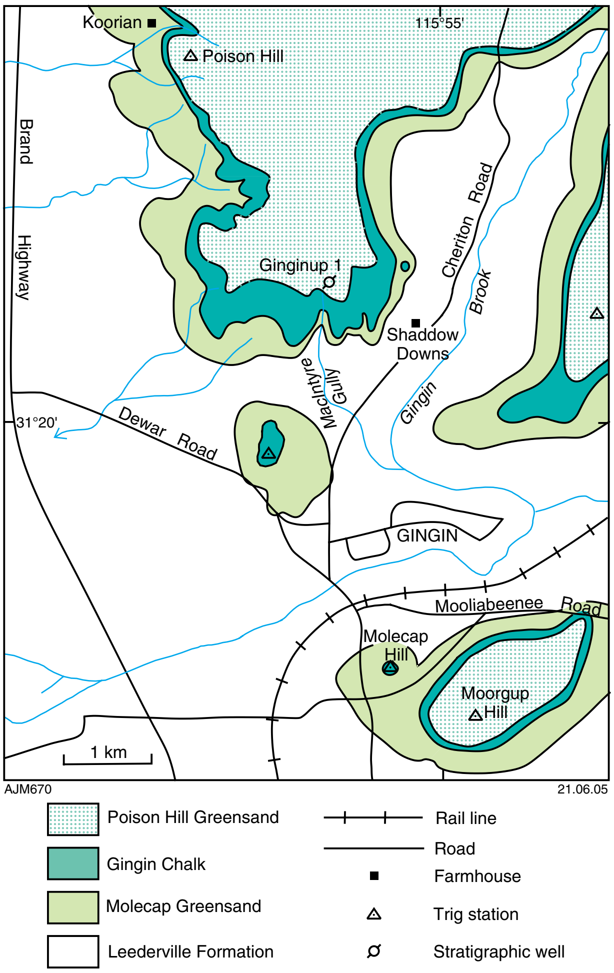

Figure 60. Pre-Cenozoic geology of the Gingin area (after Feldmann, 1963)

The Gingin Chalk contains an abundant foraminiferal fauna, for which the succession of datum levels is remarkably consistent with that in the Southern Carnarvon Platform 600 to 1000 km to the north. This suggests that the Gingin region was subject to similar oceanographic conditions and to a similar sea-level history in the Late Cretaceous.

The Santonian–Campanian age of the Gingin Chalk type section is based on (1) the occurrence of the crinoids *Uintacrinus socialis* (below about 4 m) followed by *Marsupites* (including typical *M. testudinarius*) to about 6 m in the type section (Withers, 1924, 1926; Feldtmann, 1963); and (2) the presence of the nannofossils *Calculites obscurus* at 5.1 m and above; and *Broinsonia parca* at 20.5 m and above (Shafik, 1990).

As noted by Gale et al. (1995), the first appearance of *B. parca* in the Gingin Chalk type section lies above the last appearance of *Marsupites* in the same order as for successions in Europe and North America. Of the other six biostratigraphic events recognized by Gale et al. (1995) for the Late Santonian – earliest Campanian, only the first occurrence of *C. obscurus* above the first appearance of *U. socialis* is supported by the Gingin evidence; however at the Gingin Chalk Type section, *C. obscurus* apparently first appears within the *Marsupites testudinarius* Zone rather than within the lower *Uintacrinus socialis* Zone. Burnett (1998) placed the first appearance of consistent *C. obscurus* in her Zone UC11c in both Northern Europe and in the Indian Ocean. She correlated this level with the Lower Santonian below the first appearance of *Uintacrinus socialis* (taken by her as marking the Middle Santonian). The first appearance of *B. parca* was used by Burnett (1998) to mark the base of Zone UC14 in the Indian Ocean, and was placed in the middle of the 'Lower Lower Campanian'. Burnett (1998) took the extinction of *Marsupites* to mark the Santonian–Campanian boundary.

Hancock and Gale (1996) provisionally recommended that the Santonian–Campanian boundary be placed at the extinction level of the crinoid *Marsupites testudinarius*. Lamolda and Hancock (1996) suggested that the base of the Upper Santonian be placed at the first occurrence of *Uintacrinus socialis*. These criteria would place the lowest 6 m of the Gingin Chalk type section within the Upper Santonian, and the remainder of the section in the Lower Campanian (the assignment of these ages is discussed further under Locality 4).

The underlying Molecap Greensand in Ginginup 1, ranges from the Cenomanian into the lower Santonian according to the unpublished dinocyst zonation of

Table 7. Cretaceous stratigraphy (Coolyena Group), Gingin area

Age	*Formation*	*Thickness*	*Main features*	*Environment of deposition*
mid-Santonian – Maastrichtian	Lancelin Formation	up to 120 m	chalk laterally equivalent to the Poison Hill Greensand plus Gingin Chalk; known only from subsurface west of Gingin	mid- to inner neritic
mid-Campanian – Maastrichtian	Poison Hill Greensand	up to 54 m	massive bioturbated and cross-bedded quartz and glauconite sandstone	shallow marine
Upper Santonian – Lower Campanian	Gingin Chalk	21 m	fossiliferous, bioturbated chalk, locally glauconitic	mid-neritic
Cenomanian to lower Santonian	Molecap Greensand	10–12 m	massive quartz and glauconite sandstone; unconformable on Warnbro Group in outcrop	shallow marine
Albian– Cenomanian	Osborne Formation	60–180 m	glauconitic sandstone, siltstone and claystone, unconformable on Warnbro Group; present in subsurface east of main outcrops near Gingin	shallow marine

Marshall (1985). The boundary between the Molecap Greensand and the Gingin Chalk is highly irregular over short distances. In places, the greensand is missing, and the Gingin Chalk lies directly on the Leederville Formation (Playford et al., 1976) but this is not evident close to Gingin where the Molecap Greensand sits on the Leederville Formation.

Dentith et al. (1999) suggested that the Yallalie structure, 100 km north of Gingin may be an impact crater, which formed between deposition of the Molecap Greensand and Gingin Chalk. This may explain the undulating topography of the contact between these two formations as well as the composition, lack of bedding, and mixture of fossils in the Molecap Greensand. Presumably an impact on a broad, low-gradient continental shelf, in water of around 100 m deep, could have propagated waves generating currents that mixed siliciclastic and authigenic sediment derived from different facies and deposited these rapidly leaving an undulating sea floor.

Locality 35: MacIntyre Gully

Summary: Type section of fossiliferous marine facies of Upper Cretaceous Gingin Chalk.

Location: About 2.5 km north of Gingin; MGA 395670E 6534280 to MGA 395620E 6534520N, GINGIN.

Access: The section is on 'Shaddow Downs' (formerly 'Strathalbyn') on the northwest side of Cheriton Road, 2.9 km north of the post office. Access to the gully is via a farm track 200 m north of the main entrance of the property. The track leads northwest and then to the southwest along the side of the ridge east of the gully. Enter the paddock through the gate at MGA 396040E 6354450N and park near the top of the ridge. The steep slopes are slippery when wet, and it is advisable to examine the state of the large earth dam at the top of the gully beforehand, as it may fail. Note that in winter some of the farm tracks may be impassable when the ground is wet, even to four-wheel drive vehicles, and that in summer months the owners do not allow low-clearance vehicles to cross paddocks because of the risk of fire. Contact V. and C. Schofield ('Shaddow Downs' Cheriton Rd, Gingin, 6503, ph. 08 9575 2243, fax 08 9575 2285) for access. A more accessible outcrop of the chalk is in the low road cutting 2.4 km east of Molecap Hill on Mooliabeenee Road at MGA 398590E 6530980N.

Geology: The 21 m-thick type section of the Gingin Chalk in MacIntyre Gully (Fig. 61) is the most complete exposure of this unit. The Gingin Chalk overlies the Molecap Greensand and is overlain by the Poison Hill Greensand just above the highest dam. The Gingin Chalk type section is significant in relation to the debate about the position of the Santonian–Campanian boundary (see discussion above).

The Molecap Greensand is a massive unit composed mainly of a seemingly anomalous association of coarse- to granule-sized quartz, and medium-sized dark green glauconite, implying unusual depositional processes. In MacIntyre Gully, the formation has a thickness of about 7 m. The glauconite is dark green, rounded, and crossed by shrinkage cracks infilled with cream clay. The quartz includes at least four different quartz grain populations (very well rounded, clear grains with frosted surfaces; irregularly shaped clear grains with subrounded to subangular edges; tabular clear grains; amber-coloured grains of various shapes). No carbonate biogenic sand grains are present, although there is fish debris (teeth, scale and small bone fragments) in the unit. Lundelius and Warne (1960) reported mosasaur remains from the upper 2 m of the unit in this section, and Feldtmann (1963) reported small 'saurian' limb bones from much the same level (about 1.5 m below the top of the unit). Rare ichthyosaur, and plesiosaur remains have been reported in the formation from west of Dandaragan (Teichert and Matheson, 1944; Long and Cruickshank, 1998).

The Gingin Chalk contains a high proportion of medium-sized glauconite grains, and coarse- to granule-

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Figure 61. General view of Gingin Chalk, MacIntyre Gully, Gingin (looking south from MGA 395650E 6534500N)

sized quartz grains similar to that in the underlying Molecap Greensand. The basal unit (about 2.5 m thick) of the chalk is characterized by clasts of chalk (most about 1–2 cm) set in a glauconite–quartz–chalk matrix. Above this level, the chalk is intensely bioturbated. Between 5 and 15 m, there are scattered fragments of large *Inoceramus* shells, commonly in layers, in the massive bioturbated chalk. At MacIntyre Gully, the Gingin Chalk apparently was deposited in a hollow on an undulating Molecap Greensand surface. The foraminiferal assemblage suggests deposition at water depths of 100 to 200 m. The persistent abundance of quartz and glauconite similar to that in the Molecap Greensand suggests that these grains were transported from nearby submarine exposures of Molecap Greensand. The intraformational breccia at the base of the Gingin Chalk in MacIntyre Gully indicates reworking of chalk; and the massive nature of the 2.5 m-thick deposit probably reflects rapid deposition of this basal unit (although there is some differentiation of foraminiferal assemblages within it). Extensive bioturbation masks bedding features in the remainder of the Gingin Chalk. There are undoubtedly omission surfaces throughout the section, but these are difficult to identify.

The contact between the Gingin Chalk and the overlying Poison Hill Greensand is exposed on the west side of the dam at the top of MacIntyre Gully when the waterlevel is low. Outcrops of Poison Hill Greensand on the ridge above the gully are ferruginized.

Locality 36: Molecap Hill

Summary: Quarry containing type section of shallow-marine facies of the Upper Cretaceous Molecap Greensand.

Location: About 1.4 km south of Gingin, MGA 396490E 6530440N, Gingin.

Access: Park at the end of Quin Street (off Cockram Road), about 700 m south of the rail crossing, and walk 400 m south up the hill to the quarry just east of the water tank. Contact L. Heal (Roy Weston Corporate, ph. 08 9388 6600) regarding access. The surrounding paddock is to be developed for housing with the quarry kept as a public open space. The site is registered with the National Estate (Place ID: 18167).

Geology: The quarry is the type section of the Molecap Greensand and exposes flat-lying greensand and glauconitic sandstone with phosphate (apatite, dufrenite and vivianite) nodules near the top (Marston, 1975). The greensand contains an unusual admixture of coarse-grained quartz and medium- to coarse-grained glauconite grains. Carroll (1941) suggested the heavy mineral assemblage is derived from the Chittering Valley, a tributary of Gingin Brook, but implied that the well-rounded quartz grains are recycled. About 18 m of fossiliferous, friable, slightly glauconitic Gingin Chalk disconformably overlies the Molecap Greensand near this locality, but only about

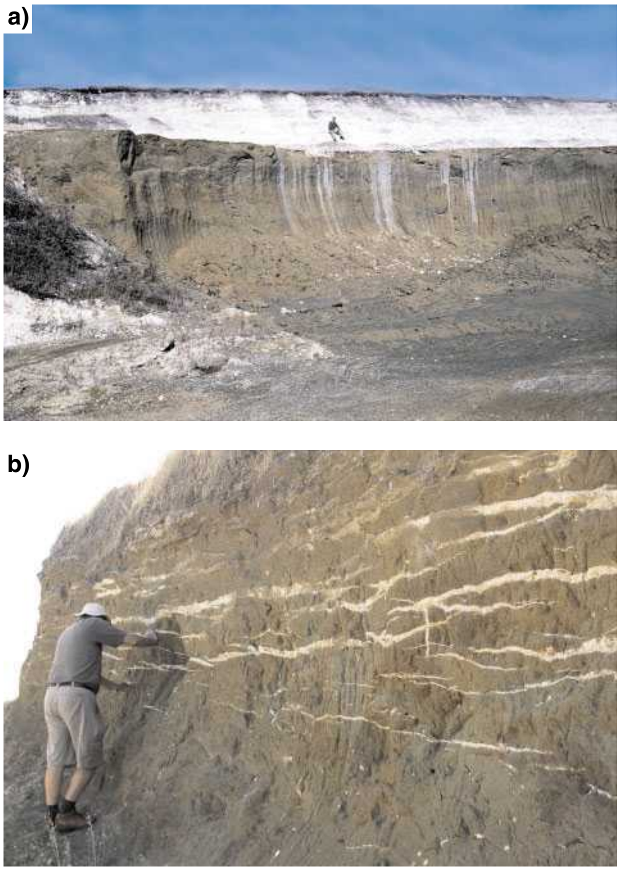

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Figure 62. Molecap Greensand, Molecap Hill quarry, Gingin: a) southern face showing contact with Gingin Chalk (photograph from the Australian Heritage Photographic Library, taken by T. E. Perrigo in 1987); b) eastern face showing veins parallel to topography and minor vertical rootlets filled with chalk (MGA 396490E 6530440N)

one metre is exposed on the southern edge of the quarry (Fig. 62a,b). The only macrofossils known from the greensand are from two 60 cm-thick phosphate-rich nodule beds near the top and floor of the quarry, and include a theropod dinosaur bone (Long, 1995), and rare shark teeth and bones. The lower nodule bed at the base of the quarry is no longer exposed.

Nearby drilling indicates the Molecap Greensand is about 11 m thick (Low, 1965), but the palynomorphs recovered were sparse and indicated only a general Cretaceous age (Edgell, 1964c). By comparison the assemblage of dinocysts Deflandre and Cookson (1955) described from 'Gingin, Molecap Hill. Lower Greensand' included '*Paleohystrichophora multispina*' (now *Diconodinium multispinum*) and "*Hystrichosphaeridium striatoconus*" (now *Conosphaeridium striatoconus*). *D. multispinum* is the index for the Cenomanian *D. multispinum* Zone but also ranges into the Turonian, whereas *C. striatoconus* is the index for, and is confined to, the Coniacian *C. striatoconus* Zone (Helby et al., 1987), thereby indicating mixing of at least Cenomanian through Coniacian in Deflandre and Cookson's (1955) material, as well as terrestrial plant and marine plankton. Marshall (1985) similarly recovered Cenomanian to Coniacian palynomorphs from this unit in Ginginup 1. This mixed fauna, as well as the mixture of terrestrial and marine vertebrates, and quartz and glauconite grains, is possibly related to slumping induced by the Yallalie impact 110 km to the north (Locality 34).

Foraminiferal correlations indicate that the base of the Gingin Chalk at Molecap Quarry is younger than the base of the formation at the type section in MacIntyre Gully. It correlates to a level about 10 m above the formation base in the type section with almost all of the Santonian part of the chalk missing at Molecap Hill.

During 1932–1962, 32 512 t of greensand were removed from the quarry, from which 6510 t of glauconite was extracted for use as a water softening agent (Low, 1971).

Locality 37: Poison Hill

Summary: Ridge containing type section of shallow marine facies of the Upper Cretaceous Poison Hill Greensand.

Location: About 6 km north-northwest of Gingin, MGA 394180E 6537310N, GINGIN.

Access: Ridge immediately south of the 'Koorian' farmhouse off the Brand Highway, 4.2 km north of Dewar Road (northern access to Gingin). Contact R. Moltoni (ph. 08 6241 4100) beforehand regarding access. Note that smoking is not allowed on the property because of the risk of fire.

Geology: This is the type section of the Poison Hill Greensand, which lies conformably on the Gingin Chalk although the basal 4 m of the unit are covered, according to Playford et al. (1976). Their description indicates that the section is composed of medium-grained to granule, glauconitic quartz sandstone, which is bioturbated in the lower 5 m exposed and thinly cross-bedded in the upper

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Figure 63. General view of Poison Hill Greensand, Poison Hill, from the north (photograph taken from MGA 394700E 6537500N)

14 m. The upper part of the unit is strongly ferruginized, and the top of the greensand is obscured by duricrust in this section (Playford et al., 1976), which presumably lies on the south side of the ridge because of the large amount of slumped material below the northern cliff face (Fig. 63). In other sections the unit rests on the 'Dandaragan Sandstone' or Leederville Formation (Warnbro Group).

No macrofauna has been found but abundant spores, pollen and microplankton are known from the unit in the subsurface (Playford et al., 1976). Edgell (1964b) obtained Campanian palynomorphs from the unit (35 – 36.5 m) in a shallow drillhole on Poison Hill that spudded in duricrust 1.5 m above the greensand. He is cited in Playford et al. (1976) as suggesting that the unit extends into the Maastrichtian, although there appear to be no microplankton of that age. The drillhole penetrated 40 m of greensand but it is unclear if the underlying unit was reached, although this thickness is compatible with that in Ginginup 1 (53.6 m), 3 km to the southeast (Ingram and Cockbain, 1979), and both holes appear to have been drilled at a similar height above sea level.

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Appendix 1

Type sections, northern Perth Basin

Unit	*Location*	*MGA coordinates (m)* *Easting*	*Northing*	*Age*	*Comments*	*References*
Alinga Formation	Alinga Point, Murchison House Station, Kalbarri area	220800	6940200	early to mid-Albian	upper part removed by pre-Toolonga Calcilutite erosion; more complete section at Locality 4B, Yalthoo Field	Clarke and Teichert (1948); Johnstone et al. (1958); Hocking et al. (1987)
Arranoo Sandstone Member (Kockatea Shale)	Dongara 24 (1451–1529 m)	307395	6764245	Early Triassic	continuously cored 1460–1529 m (cores 1–9); half split held at DoIR Perth core library	Mory and Iasky (1996)
Beekeeper Formation	Woodada 1 (2239–2353 m)	320284	6702528	Late Permian	not cored	Hall and Kneale (1992)
Bookara Sandstone Member (Kockatea Shale)	Dongara 5 (1497–1508 m)	304078	6769589	Early Triassic	not cored	Playford et al. (1976)
Bringo Shale	Bringo rail cutting, Geraldton area	289860	6818000	Early Jurassic	see Locality 16, Bringo, Geraldton area	P. E. Playford (1959); Playford et al. (1976)
Cadda Formation	Cadda Springs, Hill River area	333600	6635100	Middle Jurassic	poor exposure; upper and lower contacts covered	Playford and Willmott (in McWhae et al., 1958); Playford et al. (1976)
Carynginia Formation	Carynginia Gully, off North Branch, Irwin River, near Coalseam Conservation Park, Mingenew area	360950 to 359950	6799800 to 6799950	Early Permian	discontinuous exposure along east limb of syncline; better exposures on North and South Branches, Irwin River; see Locality 24, Coalseam Conservation Park, Mingenew area	Playford and Willmott (in McWhae et al., 1958); Playford et al. (1976); Le Blanc Smith and Mory (1995)
Carynginia Formation (reference section)	Woolaga Creek to Red Hill, Mingenew area	369290 to 370800	6769940 to 6770900	Early Permian	see Locality 25, Woolaga Creek, Mingenew area	Playford and Willmott (in McWhae et al., 1958); G. Playford (1959); Playford et al. (1976); Le Blanc Smith and Mory (1995)
Carynginia Formation (reference section)	CRAE IRCH 1 (22–92 m)	363400	6785250	Early Permian	held at DoIR Perth core library	Le Blanc Smith and Mory (1995)
Cattamarra Coal Measures	Eneabba 1 (1790–2302 m)	338585	6727781	Early Jurassic	no core in this interval	Playford et al. (1976); Mory (1994a,b)
‘Cockleshell Gully Sandstone’	Cockleshell Gully, Hill River area	325750	6665650	Early Jurassic	name abandoned when Eneabba and Cattamarra Coal Measures Members were given formation status (Mory, 1994a,b)	Playford, Willmott, and McKellar (in McWhae et al., 1958); Playford et al. (1976)

Appendix 1 (continued)

Unit	*Location*	*MGA coordinates (m)* *Easting*	*Northing*	*Age*	*Comments*	*References*
'Cockleshell Gully Sandstone' (reference section)	Cockleshell Gully, Hill River area	335800	6650700	Early Jurassic	see above	see above
Colalura Sandstone	Spion Kop, Moonyoonooka farm, Geraldton area	286030	6814680	Early Jurassic	see Locality 21, Moonyoonooka, Geraldton area	P. E. Playford (1959); Playford et al. (1976)
'Dandaragan Sandstone'	Hole-in-the-wall phosphate deposit, west of Dandaragan	370040	6603920	No diagnostic fossils	considered Aptian and a correlative of the Leederville Formation (Warnbro Group) by Playford et al. (1976), whereas Moncrieff (1989) suggested it is the basal unit of the Coolyena Group implying an Albian age; the name has fallen into disuse	Willmott and McKellar (in McWhae, 1958)
Dongara Sandstone	Dongara 11 (1682–1701 m)	306677	6760854	Late Permian	pieces of half core from cores 1 (1685.2 – 1692.9 m) and 2 (1693.5 – 1702.6 m) held at DoIR Perth core library	Mory and Iasky (1996); Tupper et al. (1994)
Eneabba Formation	Eneabba 1 (2302–2978 m)	338585	6727781	Early Jurassic	no core in this interval	Playford et al. (1976); Mory (1994a,b)
Fossil Cliff Member (Holmwood Shale)	Fossil Cliff, Coalseam Conservation Park, Mingenew area	358440	6797365	Early Permian	see Locality 24, Coalseam Conservation Park, Mingenew area	Playford et al. (1976); Le Blanc Smith and Mory (1995)
Gingin Chalk	MacIntyre Gully, Gingin area	395500	6534900	Late Cretaceous	see Locality 35, MacIntyre Gully, Gingin area	Feldtmann (1963); Playford et al. (1976)
Greenough Sandstone	Moonyoonooka farm, Geraldton area	285180	6813550	Early Jurassic	see Locality 21, Moonyoonooka, Geraldton area	P. E. Playford (1959); Playford et al. (1976)
High Cliff Sandstone	High Cliff, Coalseam Conservation Park, Mingenew area	358580	6797235	Early Permian	see Locality 24, Coalseam Conservation Park, Mingenew area	Clarke et al. (1951); Playford et al.(1976); Le Blanc Smith and Mory (1995)
Holmwood Shale	Beckett Gully, near Irwin River, Mingenew area	356250 to 358550	6788750 to 6789650	Early Permian	moderately continuous low outcrop but cut by several faults; large covered interval near lower contact	Clarke et al. (1951); Playford et al. (1976); Le Blanc Smith and Mory (1995)
Hovea Member (Kockatea Shale)	Hovea 3 (1964.6 – 1992.3 m)	309788	6755192	Early Triassic	continuously cored from 1968.6 m; quarter split held at DoIR Perth core library	Thomas et al. (2004)

Appendix 1 (continued)

Unit	*Location*	*MGA coordinates (m)* *Easting*	*Northing*	*Age*	*Comments*	*References*
'Indarra Beds'	47¼-mile bore (290–432 m)	329670	6827990	Mid–Late Permian	no samples available; name abandoned in favour of Wagina Sandstone by Playford et al. (1976)	Playford and Willmott (in McWhae et al., 1958)
Irwin River Coal Measures	North Branch, Irwin River, Coalseam Conservation Park, Mingenew area	358540 to 358810	6797930 to 6798120	Early Permian	see Locality 24, Coalseam Conservation Park, Mingenew area	Clarke et al. (1951); Playford et al. (1976); Le Blanc Smith and Mory (1995)
Irwin River Coal Measures (reference section)	CRAE IRCH 1 (92–153 m)	363400	6785250	Early Permian	held at DoIR Perth core library	Le Blanc Smith and Mory (1995)
Kockatea Shale	Kockatea Gully, near Greenough River	320550	6840230	Early Triassic	poorly exposed; better exposures in Northampton area	Playford and Willmott (in McWhae et al., 1958); Playford et al. (1976)
Kojarena Sandstone	Bringo rail cutting, Geraldton area	289900	6818100	Mid-Jurassic	see Locality 16, Bringo, Geraldton area	P. E. Playford (1959); Playford et al. (1976)
Lancelin Formation	Lancelin 2B water bore (32–46 m)	340070	6561940	Late Cretaceous	only cuttings available; unit restricted to subsurface	Edgell (1964d); Morgan (1965)
Lesueur Sandstone	Woolmulla 1 (429–1012 m)	325865	6677040	Late Jurassic	half split of cores 3–7 (up to 5.5 m each) held at DoIR Perth core library	Playford et al. (1976); Mory and Iasky (1996)
'Michin Siltstone'	Mount Michin, Northampton area	254200	6870375	Early Triassic	name abandoned in favour of Kockatea Shale by Playford et al. (1976); originally tentatively considered Early Jurassic in age	Johnstone and Playford (in McWhae et al., 1958)
Mingenew Formation	Simpson Knolls, Mingenew area	351100	6769300	Early Permian	poor exposures; fossiliferous	Playford et al. (1976)
Mingenew Formation (reference section)	Enanty Hill, Mingenew area	349800	6772300	Early Permian	poor exposures	Playford et al. (1976)
Molecap Greensand	Molecap Hill, Gingin	347970	6528790	Late Cretaceous	see Locality 36, Molecap Hill, Gingin area	Fairbridge (1953); Playford et al. (1976)
Moonyoonooka Sandstone	Moonyoonooka farm, Geraldton area	285180	6813550	Early Jurassic	see Locality 21, Moonyoonooka, Geraldton area	P. E. Playford (1959); Playford et al. (1976)
Nangetty Formation	Nangetty Hills, Mingenew area	348300	6791200	?Mid-Carboniferous to Early Permian	no specific type section; best exposures along Irwin River	Clarke et al. (1951); Playford et al. (1976); Le Blanc Smith and Mory (1995)

Appendix 1 (continued)

Unit	*Location*	*MGA coordinates (m)* *Easting*	*Northing*	*Age*	*Comments*	*References*
Newmarracarra Limestone	Round Hill, Geraldton area	285960	6816920	Middle Jurassic	see Locality 16, Bringo, Geraldton area	P. E. Playford (1959); Playford et al. (1976)
Osborne Formation	King Edward Street bore (37–133 m), Osborne Park, Perth	388240	6470180	Mid-Cretaceous (Albian–Cenomanian)	ditch cuttings only	McWhae et al. (1958); Playford et al. (1976)
Otorowiri Formation	Arrowsmith 25 water bore (253–277 m)	357910	6729720	Latest Jurassic	ditch cuttings only	Ingram (1967); Crostella and Backhouse (2000)
'Parmelia Formation'	Peel 1 (1625–3551 m)	353700	6429225	Latest Jurassic to Early Cretaceous	no core; unit raised to group by Crostella and Backhouse (2000)	Backhouse (1988); Crostella and Backhouse (2000)
Poison Hill Greensand	Poison Hill, Gingin area	393870	6536150	Late Cretaceous	see Locality 37, Poison Hill, Gingin area	Fairbridge (1953); Playford et al. (1976)
Tamala Limestone	Womerangee Hill, Zuytdorp Cliffs (Southern Carnarvon Basin)	774200[(a)]	7021100	mid- to Late Pleistocene	well exposed along coast, especially between Jurien and Dongara; see Locality 17, Cape Burney, Greenough; Locality 30, Leander Point, Port Denison; Locality 31, Jurien heavy mineral sand deposit; Locality 33, Pinnacles, Nambung National Park	Playford et al. (1976)
Toolonga Calcilutite	Yalthoo Field, Murchison House Station	225950	6943970	Lower Santonian to Lower Campanian	see Locality 4A, Yalthoo Field; reference section at Locality 4B	Clarke and Teichert (1948); Johnstone et al. (1958); Hocking et al. (1987); Lynch (1991)
Tumblagooda Sandstone	along Murchison River to Second Gully, Kalbarri area	259700 to 218000	6915300 to 6943100	?Ordovician	see Kalbarri area, **Background geology**	Hocking (1991); Iasky and Mory (1999)
Victoria Plateau Sandstone	High Cliff, Coalseam Conservation Park, Mingenew area	358580	6797235	?Late Eocene	see Locality 24, Coalseam Conservation Park, Mingenew area (Fig. 43)	Johnson et al. (1954); Playford et al. (1976)
Wagina Sandstone	South Branch, Irwin River, near Coalseam Conservation Park, Mingenew area	362100	6792250	Late Permian	Poorly exposed near Wagina Well	Clarke et al. (1951); Playford and Willmott (in McWhae et al., 1958); Playford et al. (1976); Le Blanc Smith and Mory (1995)
Wagina Sandstone (reference section)	Red Hill, Woolaga Creek, Mingenew area	370800 to 371240	6770900 to 6771900	Late Permian	see Locality 25, Woolaga Creek, Mingenew area	Playford and Willmott (in McWhae et al., 1958); Playford et al. (1976)

Appendix 1 (continued)

Unit	*Location*	*MGA coordinates (m)* *Easting*	*Northing*	*Age*	*Comments*	*References*
Wicherina Sandstone Member (Nangetty Formation)	Wicherina 1 (1308–1986 m)	328479	6809440	?Mid–Late Carboniferous	cores 5–7 (1375 – 1379.5 m, 1493.8 – 1496.9 m, 1681 – 1685.5 m) held at DoIR Perth core library	Mory and Iasky (1996)
Woodada Formation	BMR 10 (334–610 m)	304335	6698639	Early–Middle Triassic	pieces of cores 11–19 (up to 2.4 m each) held at DoIR and Geoscience Australia	Playford et al. (1976); Mory and Iasky (1996)
‘Yardarino Sandstone’	Yardarino 1 (2284–2307 m)	310944	6765857	Late Permian	half cut of cores 11–15 (2290.6 – 2293.3, 2293.9 – 2299.4, 2301.2 – 2306.4, 2306.7 – 2313.7 m) held by DoIR; name fallen into disuse	Playford and Low (1972); Playford et al. (1976)
Yarragadee Formation	Yarragadee, Mingenew area	346265 to 345950	6780320 to 6780470	Late Jurassic	see Locality 29, Yarragadee, Mingenew area	Playford et al. (in McWhae et al., 1958); Playford et al. (1976)
Yarragadee Formation (reference section)	Cantabilling Springs farm, Hill River area	332850	6652200	Late Jurassic	outcrop is discontinuous and the lower contact is faulted	Brien and McLellan (1962); Playford et al. (1976); Mory (1994a)
Yarragadee Formation (reference section)	Bringo rail cutting, Geraldton area	290100	6818760	Late Jurassic	see Locality 16, Bringo, Geraldton area	Playford et al. (in McWhae et al., 1958)
Yarragadee Formation (reference section)	Gingin 1 (356–3315 m)	388203	6553952	Late Jurassic	half split of cores 1–18 (up to 6.1 m each) held by DoIR	Backhouse (1984)

NOTES: To view or sample petroleum core contact the **Petroleum Data Release Officer** (petdata@doir.wa.gov.au); for mineral core contact wamex.datarequest@doir.wa.gov.au
(a) Zone 49
DoIR Department of Industry and Resources

Appendix 2

Locality access details

The following details are provided for localities on private land as ownership may change. Details of the owner(s) can be checked either by contacting the relevant Shire and quoting the Location or Lot number, or contacting the Department of Land Information (www.dli.wa.gov.au).

Locality	*Tenure*	*Certificate of Title number*
Shire of Northampton Hampton Road, Northampton, W.A. 6535 P.O. Box 61, Northampton, W.A. 6535 Phone: (08) 9934 1202 council@northampton.wa.gov.au		
Pencell Pool, Murchison River	vacant Crown Land, access via Victoria Location 5146	1606/745
Stone Wall, Murchison House Station	Edel Location 79	3067/234
Yalthoo Field, Murchison House Station	Edel Location 6	2103/126
Blue Hills	Victoria Location 2792	1656/86
Mount Minchin	Victoria Location 7415	1566/967
Shire of Mullewa 5 Thomas St, Mullewa, W.A. 6630 P.O. Box 166, Mullewa, W.A. 6630 Phone: (08) 9961 1007 admin@mullewa.wa.gov.au		
Kockatea Gully	Victoria Location 6520	2049/6
Bindoo Spring, Greenough River	Reserve 13993	3101/946
	striae on Victoria Location 6067	1447/565
Wenmillia Creek – Wooderarrung River	Victoria Location 3834	1363/240
	Victoria Location 3839	1624/973
Wootbeeria Pool, Wooderarrung River	vacant Crown Land, access via:	
	Victoria Location 3970	1624/966
	Victoria Location 4410	1624/969
	Victoria Location 4357	1624/973
	Victoria Location 7395	1504/229
	Victoria Location 7396	1887/562
Badgedong Creek – Wooderarrung River	vacant Crown Land, access via:	
	Victoria Location 8910	1503/164
	Victoria Location 8911	1503/164
Nangerwalla Creek	Victoria Location 4632	1457/743
Coaramooly Pool, Greenough River	Victoria Location 7088	1427/589
Shire of Greenough cnr Geraldton – Mount Magnet and Edwards Roads, Utakarra, W.A. 6530 P.O. Box 21, Geraldton, W.A. 6531 Phone: (08) 9921 0500 records@greenough.wa.gov.au		
Moonyoonooka	Lot 3	1957/331
Round Hill, west of Bringo	Lot 0	1919/50
	(previously Victoria Locations 613, 1815, and 1815)	
Sheehan Hill, Glengarry	Victoria Location 204	2132/930
	access via Victoria Location 1966	1558/144
Shire of Mingenew P.O. Box 120, Victoria St, Mingenew, W.A. 6522 Phone: (08) 9928 1102		
Irwin River, north of Depot Hill	Reserve 2360	vesting
	access via Victoria Location 687	1441/688
Yarragadee	Victoria Location 785	1400/485
	Victoria Location 1899	1401/674
Woolaga Creek	Lot 63	1511/83
	(previously Victoria Location 1909)	
	access via Lot 64	1514/82

Appendix 2 (continued)

Locality	*Tenure*	*Certificate of Title number*
Shire of Dandaragan Bashford St, Jurien Bay, W.A. 6516 Phone: (08) 9652 0800 council@dandaragan.wa.gov.au		
Jurien heavy mineral sand deposit	Melbourne Location 3750	1643/532
Shire of Gingin 7 Brockman St, Gingin, W.A. 6503 Phone: (08) 9575 2211 mail@gingin.wa.gov.au		
MacIntyre Gully	Lot 9 (previously Swan Location 398)	1278/509
Molecap Hill	Lot 505 (previously Swan Location 103)	2067/336
Poison Hill	Lot 4 (previously Swan Location 453)	2169/626

Appendix 3

Health and safety

In the event of an emergency, no site is further than one hour by road to a hospital or medical centre with ambulance services. Perth is a 1:05 hour flight from Geraldton airport with up to six flights per day compared with four flights per week into Kalbarri, the only other airport in the region with scheduled flights. Emergency response phone contacts in the region are listed in Table 3.1.

It is advisable to have a first-aid kit, and at least one person with a current senior first-aid certificate, in each vehicle. Although the area is almost entirely in farming country, some farms are not occupied. Standard digital phones should be within reach of the roaming network, but there will be occasions when you will be out of range as not all mobile phone providers have coverage in this region — CDMA phones should be usable but GSM coverage is limited. Potential hazards and suggestions for their management are listed in Table 3.2; updates to the management of common hazards can be obtained from organizations such as St John Ambulance Australia (www.stjohn.org.au) or Australian Red Cross (www.redcross.org.au).

Clothing

Sturdy field boots that protect your ankles are necessary, especially on slopes. You may need a range of clothing to provide protection from the rain, wind and sun, particularly

Table 3.1. Emergency response phone contacts

Centre	*Location*	*Phone number*
Health/ambulance		
Cervantes Nursing Post	Weston St	(08) 9652 7069
Dongara Health Centre	48 Blenheim Rd	(08) 9927 0222
Dongara Silver Chain Service Centre	48 Blenheim Rd	(08) 9927 0205
Eneabba Silver Chain Health Centre	cnr Grover and King Sts	(08) 9955 1163
Geraldton Regional Hospital	Shenton St	(08) 9956 2222
Geraldton Silver Chain Service Centre	85 Carson Tce	(08) 9921 8533
Gingin Medical Centre	Robinson St	(08) 9575 2067
Gingin Coastal Health Services	Gingin Business Centre, Brockman St	(08) 9575 2440
Jurien Bay Silver Chain Health Centre	Cook St	(08) 9652 0200
Kalbarri Health Centre	Kaiber St	(08) 9937 0100
Leeman Silver Chain Service Centre	Thomas St	(08) 9953 1038
Mingenew Silver Chain Health Centre	80 Phillip St	(08) 9928 1043
Moora District Hospital	Dandaragan Rd	(08) 9651 1403
Mullewa Health Service	Elder St	(08) 9961 1002
Northampton District Hospital	Stephen St	(08) 9934 1002
Three Springs Hospital	Thomas St	(08) 9954 1101
Police		
Carnamah	McPherson St	(08) 9951 1222
Dongara	3 Waldeck St	(08) 9927 1122
Geraldton	21 Marine Tce (24 hrs)	(08) 9923 4519
Gingin	4 Constable St	(08) 9575 2244
Jurien	Bashford St (cnr Batt St)	(08) 9652 1017
Kalbarri	48 Grey St	(08) 9937 1006
Leeman	Morcombe Rd	(08) 9953 1355
Mingenew	Williams St	(08) 9928 1103
Moora	Roberts St	(08) 9651 1106
Mullewa	Lot 87 Mills Rd	(08) 9961 1104
Northampton	Hampton Rd	(08) 9934 1103
Three Springs	cnr Carter and Maley Sts	(08) 9954 1016
Airports		
Geraldton	Geraldton – Mount Magnet Rd, Moonyoonooka	
Kalbarri	Fawcett-Broad Drive, off Kalbarri–Ajana Rd	
Flight information	Skywest Airlines	1300 660 088
	Skippers Aviation	1300 729 924

NOTES: Health details from www.health.wa.gov.au
Police details from www.police.wa.gov.au

Table 3.2. Hazards in the field

Hazard	*Management*
Abandoned shafts and adits	Do not enter or get close to edges. Watch for hidden openings
Bee stings and insect bites	Avoid swarms, which are most prevalent in spring. Hives may be present on breakaways, abandoned buildings, trees, and even fence posts. Wear long sleeves and jeans, and keep hat on near swarms. Use insect repellent for mosquitos. Remove ticks or bee stings as soon as possible
Bush fire	Depart area immediately; do not attempt to fight fire; do not drop lighted cigarettes or matches; be wary of driving across dry grassy paddocks in vehicles with low clearance during summer
Heat stress/dehydration	Hat, shade, sunscreen, water bottles
Lightning storms	Avoid high places, open fields, isolated trees, towers, light poles, metal fences, and water during storms
Local flooding	Take heed of depth markers when attempting to drive across floodways; do not cross deep, fast flowing streams by foot or vehicle
Road and rail cuttings	Watch for, and stay clear of, approaching vehicles or trains. A person should be appointed to keep watch if in a group. Do not park within road cuttings, and attach a yellow flashing light to the roof of your vehicle if within sight of approaching traffic. Orange (not red) fluorescent jackets should be worn whilst in cuttings or rail reserves. Note that it is illegal to go within 5 m of rail tracks or along rail access tracks, other than at gazetted crossings
Scree and steep slopes	Take due care and ensure ground is stable under foot. Do not cross if uncertain of your footing. Consider using a hiking stick
Snakes and spiders	Stay well clear. If you disturb a snake, stand still until it moves away
Steep rock faces and quarries	Be aware of possible loose material or overhangs. Do not stand close to edges that may crumble. Wear a hard hat. Be wary of others who may involuntarily send loose rock down a slope. Never deliberately push rocks down a slope
Waves	Watch out for large waves on coastal exposures; avoid wet surfaces
Wild animal	Stay well clear and slowly move away
Individual responsibilities:	
Alcohol/drugs	Awareness of responsibilities. Some mine sites enforce random testing and a zero tolerance policy
Back strain	Pack light, don't lift heavy objects
Car accident	Driver hazard awareness and training
Personal injuries	Bring personal protection especially sturdy boots covering ankles, long pants or gaiters, insect repellent, and sunscreen. Wear safety glasses when hammering rock
Lost	Use maps, compass, and GPS
Sickness, pre-existing conditions (including allergies)	Bring medication and a first-aid kit; be wary of hotel or fast food
Vehicle fire	Fire extinguishers — ensure they are not out of code — in vehicles; evacuate vehicle
Vehicle roadworthiness	Check water, oil, fuel, tyres, spare tyre and other items often.

NOTE: although not specifically for Australian conditions, http://www.geo-outdoors.info/field_hazards.htm or http://www.soton.ac.uk/~imw/safety.htm provide more comprehensive lists and advice

in winter and early spring when the weather is changeable. Consider bringing the following:

- sun hat, sunglasses, sunscreen, water bottle, and insect repellent;
- long sleeve shirts, jeans or long trousers, and jumper or equivalent;
- umbrella or raincoat, and gumboots.

Snake bite

Wear long trousers to minimize risk of a bite when on foot. If bitten, keep still as long as possible and immobilize the bitten limb immediately. Splinting and secure bandaging is advised, but the bitten limb should not be raised. Use a broad firm bandage to cover the entire limb, starting at the extremity using the same pressure as a bandage on sprained ankle. The bandage should not be too tight. Under no circumstances try to cut out or suck out the poison, wash the wound, or use ice or a tourniquet. Alert Emergency Services, Geraldton Regional Hospital (08 9956 2222). Bring transport to victim if feasible; do not allow victim to move around more than necessary. There is no need to kill the snake and take it with the victim.

Bee stings and insect bites

If a sting is embedded in the skin, scrape with a blunt knife rather than using tweezers to avoid squeezing more venom into the skin. Ensure that the head of any small burrowing tick is removed using fine-tipped tweezers; press skin down around the tick's embedded mouth, grip the mouth part firmly, lift gently to detach the tick — avoid squeezing the body of the tick during removal. Note that coating deeply embedded ticks with insect repellent, petroleum jelly, or methylated spirits may be more effective than using tweezers. Medical aid may be necessary if there is an allergic reaction or infection. Let others in your group know if you suffer acute allergic reactions and carry adrenaline medication if necessary.

Heat-related illness

Stop the person from continuing any activity, cool the body, and give cool, clear fluids if the victim is fully conscious. Alert Emergency Services, Geraldton Regional Hospital (08 9956 2222), call an ambulance, or transport the victim to a medical facility immediately if the victim vomits or is unconscious. Monitor the victim's condition for signs of deterioration, loosen tight clothing, and remove perspiration-soaked clothing. Cool the body by any means available: apply wet towels or cloths or cloth-covered ice packs to skin, especially around the armpits and groin; or fan the victim. Monitor the airway, breathing, and circulation, and be prepared to perform EAR or CPR.

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Further details of geological publications and maps produced by the Geological Survey of Western Australia can be obtained by contacting:

Information Centre
Department of Industry and Resources
100 Plain Street
East Perth WA 6004
Phone: (08) 9222 3459   Fax: (08) 9222 3444

www.doir.wa.gov.au/gswa/onlinepublications