4 Stratigraphy and lithology of the northern Perth Basin

Accurate identification of aquifers and aquitards intersected during drilling or well installation is essential for effective management and use of groundwater resources. This is achieved by comparing lithologic features of drill cuttings with previously published lithologic descriptions within the context of regional geology. The geological setting of the northern Perth Basin was outlined in Section 3.7. This chapter describes the stratigraphic sequence of the basin (Table 6) and provides detailed lithological descriptions of each unit and their spatial relationships. A series of maps and cross-sections show regional distribution and depth contours of the main formations. Maps are drawn on a regional scale based on the interpretation of available data and are valid at the scale presented. Spatial datasets can be requested from spatial.data@water.wa.gov.au.

The stratigraphic terminology of the Perth Basin has evolved as our understanding of the geology has improved. Relationships between the current terminology used in this bulletin and the terminology from previous reports are presented in Table 7. Some of the geological formations of the Perth Basin extend into the southern Carnarvon Basin, and the stratigraphy of these formations, and their comparable units in the Perth Basin, is shown in Table 8. Stratigraphic picks from key bores are provided in Appendix A.

The distribution of outcrop or subcrop of pre-Cenozoic geological formations is shown in Figure 18. A series of east–west geological cross-sections across the region representing the geology along each of the deep borehole lines are shown in Figure 19. Detailed lithologic descriptions of each formation are presented, beginning with the oldest formations and moving to progressively younger formations.

Sedimentation of the Perth Basin commenced with fluvial deposition in the Late Ordovician or Early Silurian (Tumblagooda Sandstone). Basin subsidence in the Early Permian was accompanied by deposition of shale and silt in a glacial marine shelf environment (Nangetty Formation, Holmwood Shale, and Carynginia Formation/Mingenew Formation) together with sand, carbonaceous shale and coal during periods of marine regression (High Cliff Sandstone and Irwin River Coal Measures). In the Early Permian, various deltaic to fluvial facies were deposited. During the Late Permian, there was a period of uplift and erosion in the northern part of the basin.

In the Early Triassic, a marine transgression in the northern Perth Basin deposited a marine shale (Kockatea Shale) followed by fluvial deposition during a regression from the Late Triassic to Early Jurassic (Woodada Formation, Lesueur Sandstone and Eneabba Formation). Within the northern part of the basin, marginal marine sediments were deposited during the later Early Jurassic (Cattamarra Coal Measures) and Middle Jurassic (Cadda Formation). The onset of major rifting during the Middle Jurassic to Early Cretaceous deposited a great thickness of sediments (Scott 1991; Mory & Iasky 1996) comprising fluvial sand (Yarragadee Formation), and extensive lacustrine clay and silt in the later stages (Otorowiri Formation and Parmelia Group).

The entire basin was uplifted and eroded during the final stage of continental breakup in the Early Cretaceous (early Valanginian age). The resulting hiatus in the sedimentary succession is referred to as the 'Breakup Unconformity' (GSWA 1990).

Following continental breakup, tectonic activity abated and the basin subsided to form a passive continental margin with episodic deposition during the Early Cretaceous in prograding shallow marine and fluvial environments (Warnbro and Winning groups) and shallow marine environments (Coolyena Group and Tooloonga Calcilutite).

A marine transgression in the Early Pleistocene or Pliocene created a series of strandlines below the Gingin Scarp (Ascot and Yoganup formations), and was subsequently followed by fluvial and lacustrine sedimentation (Guildford Formation and Bassendean Sand). Extensive carbonate dunes (Tamala Limestone) developed in the Middle Pleistocene when the coastline retreated west of its current position. The Holocene is marked by deposition of lagoonal and dune sediments representing sea levels up to 2 m higher than current levels.

Table 6 Stratigraphic sequence of the Perth Basin

Era	Period	Epoch (Ma)	Stage	Stratigraphy			Max onshore thickness (m)	Lithology	Depositional environment
Cenozoic	Quaternary	Holocene Present0.01		Superficial formations	Alluvium, estuarine and swamp deposits		~5	Clay, sand and peat	Alluvial to estuarine
					Safety Bay Sand		100	Sand	Shoreline and dune
					Becher Sand		~2	Sand	Shallow marine to shoreline
		Pleistocene 0.01–2.6			Tamala Limestone		150	Calcareous arenite, limestone, sand and clay	Dune and shoreline
					Bassendean Sand		~40	Sand, minor silt and clay	Dune
					Muchea Limestone		~2	Limestone	Lacustrine
					Guildford Formation		~30	Clay and sandy clay	Fluvial to estuarine
	Neogene	Pliocene 2.6-5.3			Yoganup Formation		21	Sand	Shoreline
					Ascot Formation		31	Sand, clay and limestone	Shallow marine
Mesozoic	*Unconformity*								
	Cretaceous	Late 65.5-100.5	Maastrichtian	Coolyena Group	Lancelin Formation	Poison Hill Greensand	59-41	Sandstone, siltstone, clay and glauconitic	Near-shore shallow marine
			Campanian			Gingin Chalk	18	Chalk, sandy and glauconitic	Shallow marine
			Santonian			Molecap Greensand	102	Sandstone, glauconitic	Shallow marine
			Coniacian						
			Turonian						

			Cenomanian		Osborne Formation	*Mirrabooka Member*	40	Sandstone, glauconitic, with siltstone and shale	Shallow marine
			Albian			*Kardinya Shale Member*	235	Siltstone and shale, minor sandstone	Marine
			Aptian – late			*Henley Sandstone Member*	48	Sandstone, minor siltstone and claystone	Shallow marine
			Unconformity						
			Aptian – earliest	Warnbro Group	Leederville Formation	*Pinjar Member*	182	Sandstone, siltstone and shale	Marine to non-marine
			Barremian			*Wanneroo Member*	390	Sandstone, with lesser siltstone and shale	Non-marine to marine
			Hauterivian Barremian			*Mariginiup Member*	205	Sandstone, siltstone and shale	Marine
					South Perth Shale		178	Siltstone and shale, minor sandstone	Marine
					Gage Sandstone		260	Sandstone, siltstone and shale	Marine
			Unconformity						
		Early 100.5 - 145.5	Berriasian	Parmelia Group	'Undifferentiated' Parmelia Group		~300	Sandstone, siltstone and shale	Fluvial to lacustrine
						Carnac Formation	450	Siltstone and shale, minor sandstone	Lacustrine
	Jurassic	Late 145.5-163.5	Tithonian					Sandstone, siltstone and shale	Fluvial to lacustrine
					Otorowiri Formation		102	Shale and siltstone, minor sandstone	Lacustrine
				Yarragadee Formation	Unit D		1741	Shale, siltstone and clayey sandstone	Lacustrine
			Kimmeridgian Oxfordian		Unit C		719	Sandstone and clayey sandstone	Fluvial
		Middle 163.5-174.1	Callovian Bathonian		Unit B		967	Siltstone, shale and sandstone	Lacustrine with fluvial intervals
			Bajocian		Unit A		1095	Sandstone, siltstone and shale	Fluvial
			Aalenian	Cadda Formation			290	Sandstone, siltstone, claystone/shale and limestone	Marine to marginal marine
		Early 174.1-201.3	Toarcian Pliensbachian	Cattamarra Coal Measures			1200	Sandstone, siltstone, shale and coal	Lacustrine to fluvial
			Sinemurian Hettangian	Eneabba Formation			854	Sandstone, siltstone and claystone	Fluvial

	Triassic	Late 201.3-237.0	Rhaetian	Lesueur Sandstone	1202	Sandstone	Fluvial
			Norian				
			Carnian				
		Middle 237.0-247.2	Ladinian				
			Anisian				
		Early 247.2-252.2		Woodada Formation	276	Sandstone and siltstone	Marine deltaic
			Olenekian	Kockatea Shale *Bookara Sandstone Member*	1061	Shale, minor siltstone and sandstone	Marine
			Induan				
Paleozoic	Permian	Late 252.2-259.8	Changhsingian	Wagina Sandstone / Dongara Sandstone / Beekeeper Formation	243, 336, 155	Sandstone, clayey sandstone, mudstone/shale and limestone	Fluvial to marine
			Wuchiapingian				
		Disconformity / Unconformity					
		Early 272.3- 298.9	Artinskian	Carynginia Formation / Mingenew Formation	337	Siltstone, claystone and sandstone	Cold shallow marine
				Irwin River Coal Measures	307	Sandstone, siltstone, shale and coal	Alluvial delta
				High Cliff Sandstone	150	Sandstone, minor siltstone	Marine deltaic to shoreline
			Sakmarian	Holmwood Shale *Fossil Cliff Member*	700	Shale, siltstone and calcarenite	Cold marine
			Asselian	Nangetty Formation *Wicherina Member*	1000	Sandy siltstone and mudstone; sandstone	Glacial to proglacial marine
	Unconformity						
	Silurian	Llandovery 433.5–443.8		Tumblagooda Sandstone	>1000	Sandstone	Fluvial to shallow marine
	Ordovician	Late 443.8–458.0					
	Unconformity						
Precambrian	Proterozoic	541.0-2500.0		Moora Group		Metasedimentary rocks	
				Yandanooka Group	>5000	Metasedimentary rocks	
			Unconformity				
				Mulligarra Inlier		Gneissic rocks	
			Unconformity				
				Northampton Inlier		Granulite, granite	

See Table 10 for surficial stratigraphy

Table 7 Stratigraphic terminology used in previous hydrogeological publications

Author	**Term**	**Current name**
Sanders (1967a, b)	Yarragadee Unit II	Warnbro Group
Sanders (1967)a, b	Yarragadee Unit I	Parmelia Group
Barnett (1969)	South Perth Formation	Parmelia and Yarragadee formations
Balleau and Passmore (1972)	Cretaceous Yarragadee Formation	Parmelia Group
Harley (1974)	Yarragadee III–VI	Parmelia Group
Playford et al. (1976)	Cockleshell Gully Formation	Eneabba Formation and Cattamarra Coal Measures
Mory (1995a)	Eneabba Member of Cockleshell Gully Formation	Eneabba Formation
Mory & Iasky (1996)	Cattamarra Coal Measures Member of Cockleshell Gully Formation	Cattamarra Coal Measures
This publication	Yarragadee Formation	Yarragadee Formation or Yarragadee units A, B, C and D
This publication	Parmelia Group	Undifferentiated Parmelia Group, Carnac and Otorowiri formations
Playford et al. (1976)	Otorowiri Siltstone Member of Yarragadee Formation	Otorowiri Formation
Playford et al. (1976)	Gage Sandstone Member of South Perth Shale	Gage Sandstone
Fairbridge (1953)	Dandaragan Sandstone	Henley Sandstone Member
Commander (1978)	Lower Yarragadee	Yarragadee Formation
Commander (1978)	Upper Yarragadee	Parmelia Group
Briese (1979a, b)	Otorowiri Siltstone Member of Yarragadee Formation	Carnac Formation
Backhouse (1984)	Parmelia Formation	Parmelia Group

Table 8 *Nomenclature correlation for Cretaceous stratigraphy between the Carnarvon and Perth basins*

Age		**Carnarvon Basin**		**Perth Basin**		
		Stratigraphy		**Stratigraphy**		
Maastrichtian			*Unconformity*	Coolyena Group	Lancelin Formation	Poison Hill Greensand
Campanian	Late					
	Early		Toolonga calcilutite			Gingin Chalk
Santonian	Late					
	Early					Molecap Greensand
Coniacian	Late					
	Early		*Unconformity*			
Turonian			Haycock Marl			
Cenomanian		Winning Group	Gearle Siltstone		Osborne Formation	Mirrabooka Member
Albian	Late		*Unconformity*			Kardinya Shale Member
	Early		Alinga Formation			
Aptian	Late		Windalia Radiolarite Windalia Sandstone Member			Henley Sandstone Member
			Unconformity	*Unconformity*		
	Earliest		Birdrong Sandstone	Warnbro Group	Leederville Formation	Pinjar Member
Barremian	Late					Wanneroo Member
	Early		*Unconformity*			
Hauterivian–Barremian						Mariginiup Member
					South Perth Shale	
					Gage Sandstone	
Valanginian				*Unconformity*		
Berriasian						

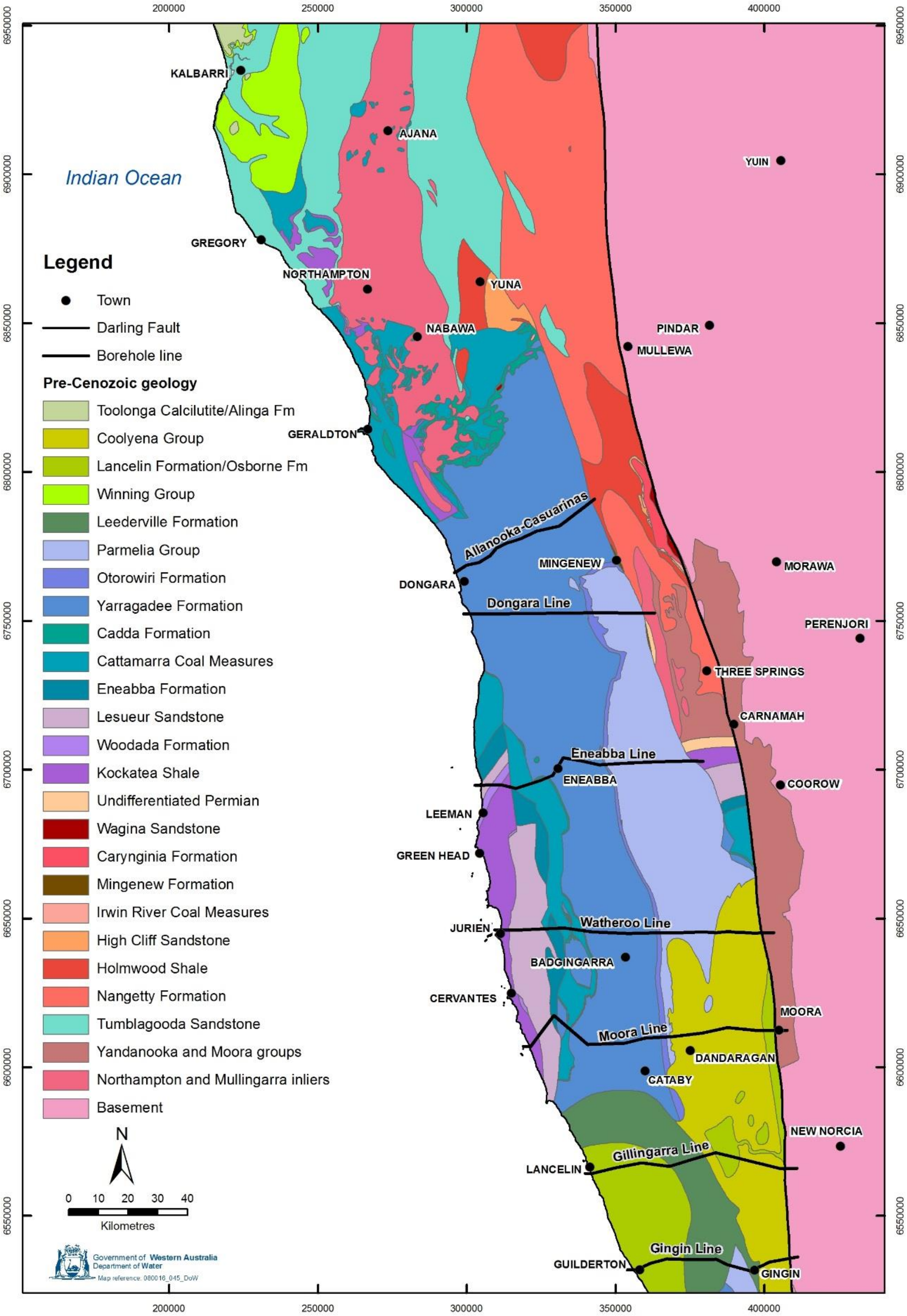

Figure 18 Regional pre-Cenozoic geology (in subcrop or outcrop)

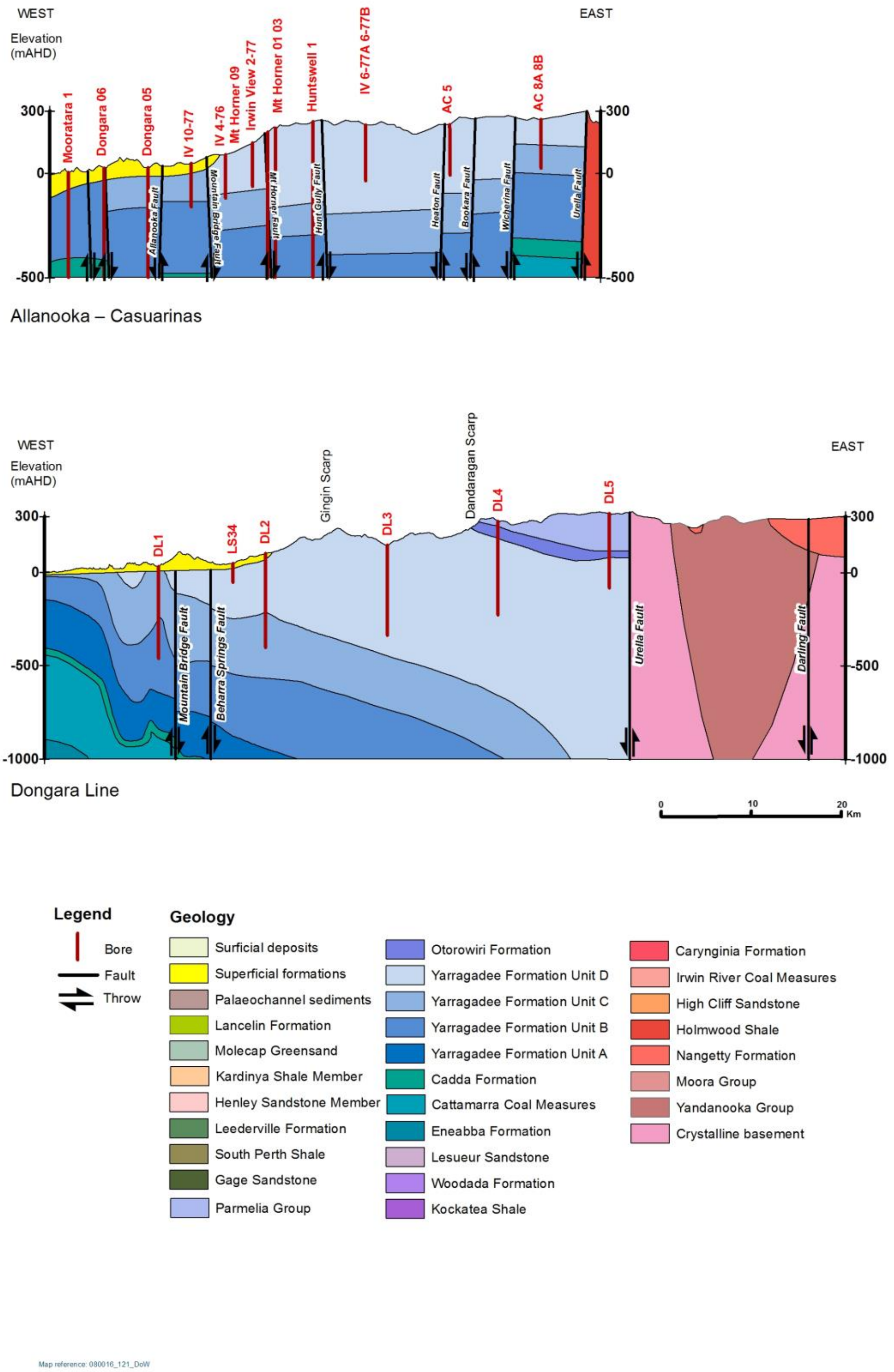

Figure 19 Geological cross-sections

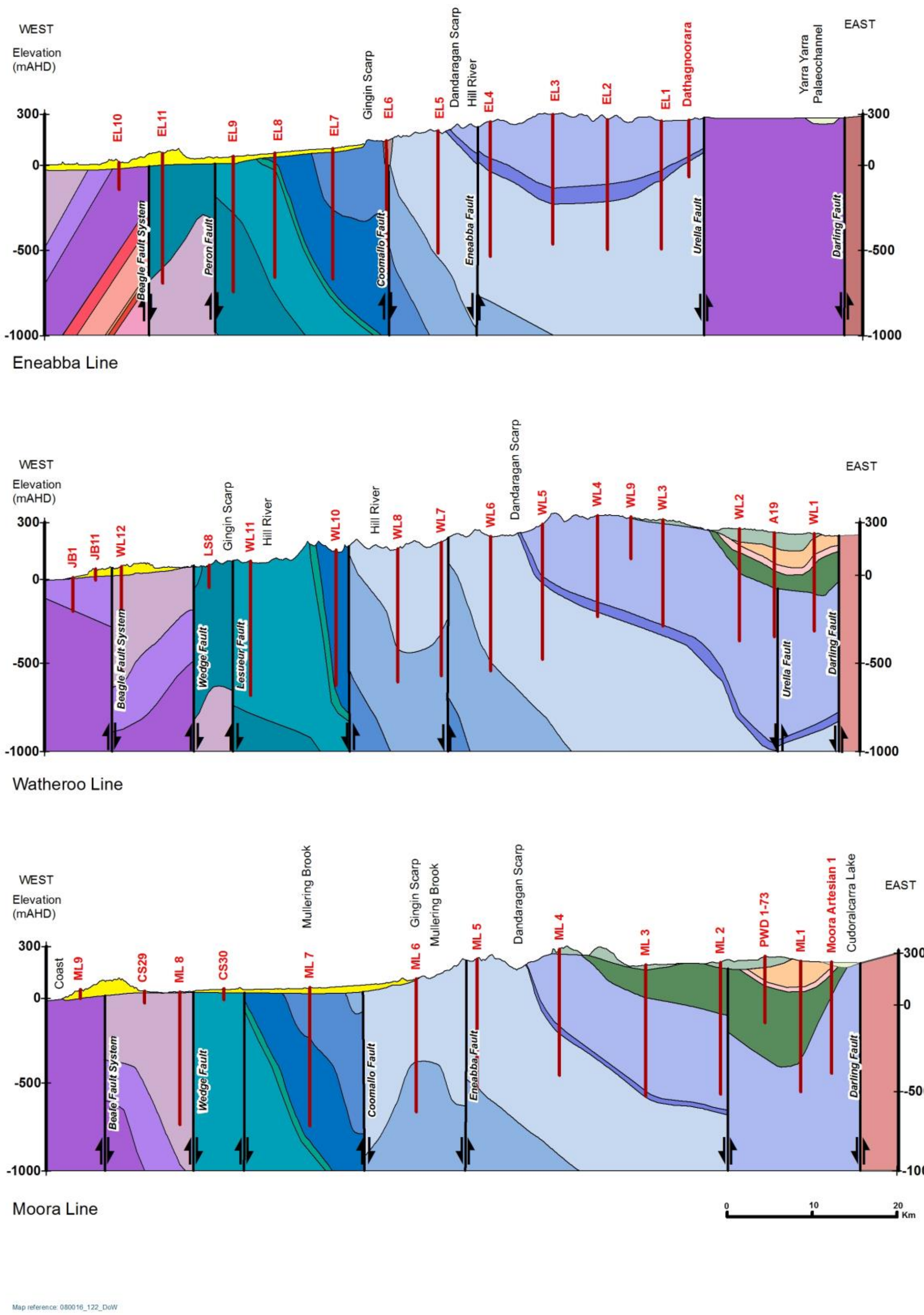

Figure 19 Geological cross-sections (continued)

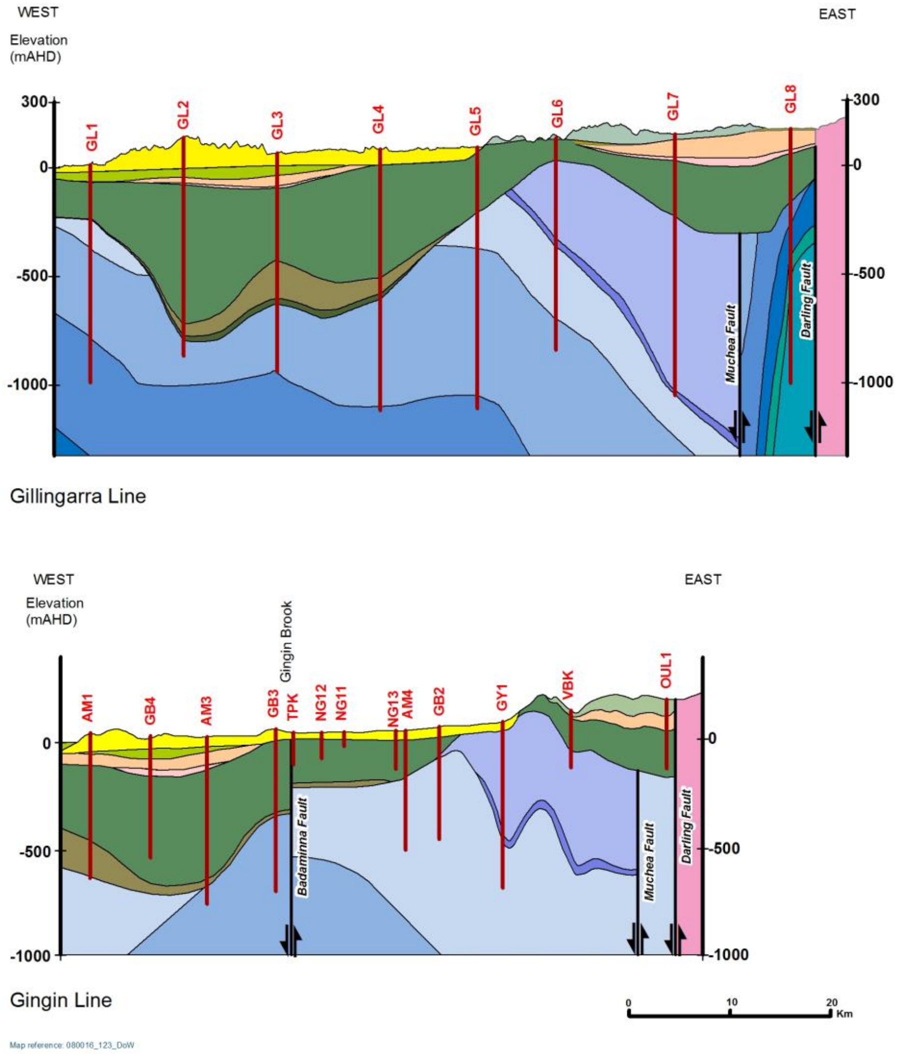

Figure 19 Geological cross-sections (continued)

4.1 Mullingarra and Northampton inliers

The Northampton Inlier was referred to as the 'Greenough Block' (Fairbridge 1951) before Hills (1965) established the term 'Northampton Block' (Daniels & Horwitz 1969). Subsequently, Myers (1990) introduced the name 'Northampton Complex'. The GSWA has recently renamed this as the Northampton Inlier (A Mory 2016, pers. comm.). Therefore, this bulletin uses Northampton Inlier as the most recent name.

The geology of the Northampton Inlier was first described by Gregory and Gregory in 1848 (*in* Hocking et al. 1982) and, subsequently, Maitland completed systematic mapping of the Northampton Mineral Field in 1903. Jones and Noldart published a description of the regional geology in 1962 (Peers 1971). Detailed descriptions for the Northampton Inlier are contained in Playford et al. (1970) and Hocking et al. (1982).

The Northampton Inlier is a structural unit comprising Mesoproterozoic granulite and granite with migmatite along the granite–granulite contact of the Pinjarra Orogen (Peers 1971). The granulites are the oldest rocks of the Northampton Inlier and formed from regional metamorphism of sediments and gabbroic sills. The granulite has gneissic banding that varies in grain size and abundance of biotite and garnet (Peers 1971; Playford et al. 1970). These are interlayered with feldspathic quartzite and pegmatite (Peers 1971). Porphyritic granite with pink microcline phenocrysts intrudes the granulites and migmatite developed along the contact with the granulite. Proterozoic dolerite dyke swarms cut through the Northampton Inlier (Playford et al. 1970; Hocking et al. 1982). These are predominantly north-east trending. The dykes are vertical or very steep, are up to 25 m wide and might persist for 16 km (Playford et al. 1970). The Northampton Inlier is onlapped by Phanerozoic sediments where the Tumblagooda Sandstone and Kockatea Shale pinch out against the Northampton Inlier. Other parts of the inlier are overlain by flat-lying Jurassic sediments of the Cadda Formation and Cattamarra Coal Measures. Remnant Jurassic sediments occur as outliers upon the Northampton Inlier such as the Nabawa Sandplain (Koomberi 1995), forming flat-topped hills commonly capped by laterite. The north-western boundary is marked by the Hardabut Fault (Playford et al. 1976) and by the Yandi Fault to the east.

The Mullingarra Inlier, first described by Baxter and Lipple (1985), is a narrow inlier of Proterozoic gneissic rocks of the Pinjarra Orogen within the Perth Basin that is bound by the Urella Fault to the west. It comprises a series of pelitic, quartzo–feldspathic and semipelitic gneisses that are collectively referred to as the Mullingarra Gneiss. Lenses of quartzite and amphibolite are contained within the gneiss as are abundant veins of pegmatite. There is a small intrusion of porphyritic granite in the north-eastern part of the Ikewah Range. The Mullingarra Inlier is onlapped by Proterozoic sedimentary rocks of the Yandanooka Group to the east and overlain by Permian sediments in the north (Baxter & Lipple 1985). The inlier outcrops between the Irwin and Yarra Yarra terraces, and abuts the Parmelia Group along the Urella Fault (Mory & Iasky 1996).

4.2 Yandanooka and Moora groups

The Yandanooka and Moora groups are metasedimentary rocks of the Proterozoic Pinjarra Orogen preserved along the margin of the Perth Basin and Yilgarn Craton. For completeness, the Moora Group is included in this bulletin, as it is equivalent to part of the Yandanooka Group, although it lies entirely outside the Perth Basin (Figure 18).

The Yandanooka Group occupies the Irwin Terrace in a shallow north-plunging syncline, resting unconformably between the Darling Fault in the east and the gneissic rocks of the Mullingarra Inlier to the west. Its southern limit is near Lake Eganu, where it has a faulted boundary beneath Cretaceous sedimentary formations. Northward, it extends beneath the Permian Nangetty Formation (Low 1975; Muhling & Low 1977; Baxter & Lipple 1985). The Yandanooka Group outcrops between the Yarra Yarra Lakes northward to Corral Creek and between Three Springs and Yandanooka (Playford et al. 1976; Baxter & Lipple 1985).

The platform sequence of Proterozoic metasedimentary rocks between Moora and Carnamah on the adjoining Yilgarn Craton is assigned to the Moora Group, the lower subgroup of which (the Billeranga Subgroup) is recognised as being laterally equivalent to the Yandanooka Group (Baxter & Lipple 1985). The Moora Group has been described by Logan and Chase (1961), Playford et al. (1976), Carter and Lipple (1982), and Baxter and Lipple (1985).

Yandanooka Group

The Yandanooka Group was originally called the Yandanooka Beds by Woolnough and Somerville (1924) and subsequently renamed the Yandanooka Group by Johnson et al. (1954). Descriptions for the Yandanooka Group are detailed in Baxter and Lipple (1985), Low (1975) and Playford et al. (1976).

Baxter and Lipple (1985) describe the Yandanooka Group as a sequence of Proterozoic clastic sedimentary rocks possibly exceeding 5000 m in thickness. Five formations are recognised within the Yandanooka Group (Playford & Willmott *in* McWhae et al. 1958; Playford et al. 1976). These are (in order from the base) the Arrowsmith Sandstone, Arrino Siltstone, Beaconsfield Conglomerate, Enokurra Sandstone and Mount Scratch Siltstone (Low 1975). Brief descriptions of these formations are provided below.

The Arrowsmith Sandstone is a well-sorted and well-bedded feldspathic quartz sandstone. The type section is 335 m thick, located 6 km south-southeast of Arrino (MGA Zone 50, 367817 m E, 6736749 m N). It rests unconformably on an Archean gneiss unit of the Mullingarra Inlier, partially infills the irregular palaeotopography of this unit (Baxter & Lipple 1985; Low 1975) and pinches out against elevated basement in places (Low 1975).

The Arrino Siltstone is a dark reddish-brown, micaceous siltstone which lies conformably on the Arrowsmith Sandstone, except where the sandstone is absent, in which case it sits unconformably on the Archean gneiss. It is a uniform sequence that is poorly to well-bedded (Low 1975) and includes some sandy beds and layers of lenticular, conglomeratic sandstone, particularly towards the base of the unit (Baxter & Lipple 1985; Low 1975). The type section of the Arrino Siltstone is 509 m thick, and is 1.6 km east-northeast of Yandanooka (MGA Zone 50, 362168 m E, 6756078 m N) (Low 1975). Where it overlies the

Archean gneiss, 4.8 km north-northeast of Yandanooka, it is only 60 m thick (Playford & Willmott 1958; Low 1975).

The Beaconsfield Conglomerate consists of rounded to poorly-rounded cobbles with weak, imbricate fabric and layers of laminated, weakly cross-bedded grit (Baxter & Lipple 1985). The unit is an epiclastic deposit and is part of the substantial volcanic activity in the source area. It conformably overlies the Arrino Siltstone, and is overlain disconformably by the Enokurra Sandstone (Low 1975). The clasts comprise cobble-sized, black to dark red and yellow-grey vesicular dacite, andesite, porphyritic basalt and fine-grained dolerite. The matrix is unsorted, fine silt to a coarse-grained sand (Baxter & Lipple 1985; Low 1975). The type section is 40 m thick and is located on Beaconsfield Creek (MGA Zone 50, 363741 E, 6759852 N) (Low 1975).

Low (1975) describes the Enokurra Sandstone as a grey, yellow, brown and pink fine-grained to very coarse grained sandstone grading into fine conglomerate in places with quartz, quartzite, andesite and siltstone, with subangular to rounded pebbles and granules. Large-scale cross-bedding is also well developed. It overlies disconformably either the Beaconsfield Conglomerate or the Arrino Siltstone.

The Mount Scratch Siltstone conformably overlies the Enokurra Sandstone, and is overlain by the Lower Permian Nangetty Formation with an angular unconformity (Low 1975). Mount Scratch Siltstone comprises a thick sequence of reddish-brown, greenish-grey and grey micaceous siltstone between 7.6 and 9.0 km thick. The siltstone is well-bedded to fissile, commonly with well-developed cross-bedding and current ripple marks. Thinner beds of fine-grained sandstone and conglomerate are present, as are andesite and trachyte clasts and minor quartz grains and granite pebbles. The type section located at Mount Scratch is 896 m thick, and starts at 11 km east-northeast of Yandanooka (MGA Zone 50, 371433 m E, 6759819 m N) and continues to the east for 0.8 km (Low 1975).

Moora Group

The Moora Group comprises a thin remnant of a previously extensive platform sequence that unconformably overlies an irregular, locally rugged Archean basement topography. It is up to 15 km wide immediately to the east of the Darling Fault. It has undergone little deformation, and metamorphism is very low grade (Baxter & Lipple 1985). Blocks of chert in the Permian Nangetty Formation suggest that the subgroup was extensively eroded during Permian glaciation.

The lower Billeranga Subgroup comprises up to 400 m of weakly deformed immature fluviatile–alluvial, fan-basin margin sediments. It is disconformably overlain by the Coomberdale Subgroup comprising undeformed sandstone, siltstone, dolomite, and silicified dolomite up to 1500 m thick. The former Coomberdale Chert is now known as the Noondine Chert.

The basal Mokadine Formation of the Coomberdale Subgroup, as redefined by Baxter and Lipple (1985), conformably overlies the Dalaroo Siltstone of the Billeranga Subgroup. It grades upward into arkose and felspathic quartzite in the lower part of the formation, becoming siltstone, mudstone and minor chert in upper parts (Logan & Chase 1961).

The conformably overlying Noondine Chert comprises interbedded sandstone and algal–carbonate cycles of bedded chert, chert breccia, orthoquartzite, silicified limestone and dolomite with minor silicified siltstone and sandstone, and claystone (Carter & Lipple 1982). Although most of the carbonate units have been extensively silicified, minor dolomite is still preserved in several horizons, including exposures at Jingemia Cave (7 km north-west of Watheroo) defined as Jingemia Dolomite (Baxter & Lipple 1985). The dolomite has been steatised at the Three Springs talc mine. Locally, the Noingara Siltstone forms thin horizons of red-brown siltstone interbedded with sandstone of the Winemaya Quartzite (Baxter & Lipple 1985), which disconformably overlies the Dalaroo Siltstone.

4.3 Tumblagooda Sandstone

The Palaeozoic Tumblagooda Sandstone is the oldest formation in the Perth Basin, and outcrops on either side of the Northampton Inlier. It was named by Clarke and Teichert (1948), who described the sequence in the lower Murchison River. The type section, defined by Johnstone and Playford (*in* McWhae et al. 1958), extends for about 70 km of the Murchison River Gorge between Hardabut Pool and Second Gully.

The Tumblagooda Sandstone is a 'red-bed' sequence of predominantly hematitic, brownish-red to purplish-brown units of quartz and feldspathic fine- to coarse-grained sandstone with some granule to pebble conglomerate (Hocking 1991). A hematite–goethite coating of grains is responsible for the colouration of the sequence (Hocking et al. 1987). Pallid, light brown and yellow horizons are present in places and these tints are largely caused by deep weathering (Hocking 1991; Kern 1993b).

The sandstone is horizontally stratified, with small to large-scale cross-bedding, and frequent bioturbation of beds. Invertebrate trails and castings are also observed, as well as rare intercalations of greenish mudstone within the sandstone (Hocking 1991). The sandstone is hard and jointed below the weathering profile (Kern 1993b). At Kalbarri, north-northeast and north-west oriented joints are observed, as well as horizontal bedding plane partings (Barnett 1980).

In the southern Carnarvon Basin, the Tumblagooda Sandstone is at least 1000 m thick (Hocking 1987), although its full extent has not been penetrated. A stratigraphic thickness of about 1210 m is present at the type section (Hocking 1991) and a thickness greater than 2600 m has been encountered in offshore drilling (Hocking 1991). In the Perth Basin, petroleum exploration well Wendy 1, located 38 km east of Northampton upon the Bookara Shelf, intersected 1098 m of Tumblagooda Sandstone below 112 m depth (Victoria Petroleum NL 2004). Playford et al. (1970) considered the Tumblagooda Sandstone to be as much as 1500 m thick on the eastern side of the Northampton Inlier.

In the Palaeozoic, the Perth and Carnarvon basins formed a broad, north-opening trough within which the Tumblagooda Sandstone was continuously deposited (Hocking 1991). It was deposited in a braided, fluviatile environment, possibly with intertidal and tidally influenced shallow marine environments (Hocking et al. 1982).

The age of the Tumblagooda Sandstone is ambiguous. It was previously considered a Silurian deposit due to invertebrate trails and castings within the formation (Hocking et al.

1985) through to Upper Silurian age for the Dirk Hartog Group (Hocking 1982), which conformably overlies the Tumblagooda Sandstone in the central part of the Gascoyne Platform (Playford et al. 1975). It now appears that the Tumblagooda Sandstone age might extend from Cambrian to Early Silurian (Mory et al. 2003), based on fauna within the overlying Dirk Hartog Group being revised to Late Ordivician to early Silurian (Mory et al. 1998).

The Tumblagooda Sandstone is present through most of the Carnarvon Basin (Hocking 1991) and extends into the northernmost portion of the Perth Basin but not south of Geraldton. The Tumblagooda Sandstone unconformably overlies crystalline basement.

Within the central part of the Carnarvon Basin, the Tumblagooda Sandstone is overlain conformably or disconformably by the Dirk Hartog Group (Mory et al. 2003) but this group does not extend into the southern portion of the basin. South of the Murchison River, the Tumblagooda Sandstone is unconformably overlain by the Cretaceous Winning Group. Further south, near the south-western limit of the onshore Carnarvon Basin and into the Perth Basin, it is unconformably overlain by the Triassic Kockatea Shale or the Jurassic Cattamarra Coal Measures. In the Perth Basin, east of the Urella Fault on the Irwin and Coolcalalaya terraces, the Tumblagooda Sandstone is unconformably overlain by Carboniferous–Permian sediments of the Nangetty Formation.

The Tumblagooda Sandstone is concealed by a thin surficial cover to the east and west of the Northampton Inlier. Extensive outcrops are present within the Murchison River Gorge and as coastal cliffs south of Kalbarri. There are also small outcrops at the western and eastern margins of the Northampton Inlier as far south as Northern Gully near Wicherina, and east of the Urella Fault, near Bindoo Hill in the Perth Basin.

4.4 Nangetty Formation

The Nangetty Formation is a glacigene unit at the base of the Permian sequence, representing the start of continuing sedimentation in the Perth Basin through to the Late Cretaceous. The name was introduced by Clarke et al. (1951) as the ‘Nangetty Glacial Formation’, and amended by Playford and Willmott *in* McWhae et al. (1958) to the Nangetty Formation. The type area is located in the Nangetty Hills (MGA Zone 50, 348500 m E, 6791000 m N), 5 m between the Irwin River and Nangetty Creek about 20 km north of Mingenew. The formation outcrops across the Irwin Terrace (Mory & Iasky 1996) and Coolcalalaya Terrace (van de Graaff et al. 1980; Hocking et al. 1982) and the main exposures are within the Lockier and Irwin rivers. However, there is no specific type section because exposure is poor and discontinuous (Playford et al. 1976). Nangetty Formation lithostratigraphic equivalents are found over large parts of Gondwana. The formation is equivalent to the Shotts Formation in the Collie Basin (Le Blanc Smith & Mory 1995, Mory & Iasky 1996) and the Lyons Group in the Carnarvon Basin (Hocking et al. 1982).

The dominant lithology of the Nangetty Formation is pale greenish grey to blue-green laminated sandy siltstone and mudstone (Le Blanc Smith & Mory 1995; Mory & Iasky 1996). In outcrop, it is often weathered to a medium brown colour (Mory & Iasky 1996). Occasional erratic boulders up to 6 m diameter deposited by melting icebergs, and some large spherical limestone concretions are present (Playford et al. 1976; Le Blanc Smith & Mory 1995). The boulders comprise igneous, metamorphic, and sedimentary Archean and Proterozoic rocks, including rocks from the Yandanooka Group and Moora Group (Playford et al. 1976; Le Blanc Smith & Mory 1995). Some boulders show surface faceting and striations, indicating glacial deposition.

A sandstone bed, present at the base of the Nangetty Formation, has been formally defined as the Wicherina Sandstone Member (Mory & Iasky 1996). This comprises white, fine- to coarse-grained quartz sandstone with minor carbonaceous strips and some conglomerate (Mory 1995). The Wicherina Sandstone Member is tentatively correlated with the Harris Sandstone near the base of the Lyons Group in the Carnarvon Basin (Mory 1995). The designated type section is the interval member from 1308 to 1686 m bgl in petroleum well Wicherina 1 (Mory 1995). This is also the thickest section encountered. Representative downhole gamma-ray logs through the Nangetty Formation are shown in Figure 20 and Figure 21.

The Nangetty Formation was deposited in a glacial to proglacial marine shelf setting (Le Blanc Smith & Mory 1995). The sandstones of the Wicherina Member at the base of the formation represent continental moraine and high-energy fluvioglacial channel deposits (Baxter & Lipple 1985; Mory & Iasky 1996). The transition to the overlying siltstone and mudstone resulted from a transgression to lacustrine and probably marine conditions (Baxter & Lipple 1985). Palynomorphs from the upper Nangetty Formation and overlying Holmwood Shale are of Asselian age from the Early Permian (Backhouse 1992c, 1993a) placing the formation near the Carboniferous–Permian boundary.

The Nangetty Formation is thickest in the east towards the Darling Fault, exceeding 1000 m upon the Irwin Terrace (Le Blanc Smith & Mory 1995). It thins to the west and south over the Allanooka High towards the Dongara Terrace and Greenough Shelf, and is absent over the Beagle Ridge and the western part of the Cadda Terrace (Mory & Iasky 1996). Within the Dandaragan Trough, the formation is too deep to have been intersected by drilling or identified on seismic profiles. However, within the Greenough Shelf, seismic profiles show that the Wicherina Member is about 250 m thick along the western side of the Dongara gas and oilfield, with a maximum intersected thickness of 378 m in petroleum well Wicherina 1 (Mory & Iasky 1996).

The Nangetty Formation unconformably overlies Proterozoic and Archean basement rocks, the Yandanooka Group and the Tumblagooda Sandstone. It is conformably overlain by the Holmwood Shale with an apparent gradational contact from pale greenish grey silts to blue-blackish shale, a decrease of erratics and the prevalence of mica in the shale (Le Blanc Smith & Mory 1995; Mory & Iasky 1996).

4.5 Holmwood Shale

The Holmwood Shale is an Early Permian siltstone and shale deposit comprising three members with thin beds of fossiliferous limestone named, in ascending order, the Beckett, Woolaga Creek Limestone and Fossil Cliff members (Playford et al. 1976; Le Blanc Smith & Mory 1995). Clarke et al. (1951) introduced the Holmwood Shale, named after the Holmwood homestead south of the Irwin River near the Darling Fault, and Playford and Willmott (*in* McWhae et al. 1958) nominated a type section nearby along Beckett Gully (MGA Zone 50, 356141 m E, 6789037 m N). The Fossil Cliff Member at the top of the formation was originally defined as a separate formation (Clarke et al. 1951), but was later incorporated as a member of the Holmwood Shale (Johnson et al. 1954; Playford et al. 1976) as it is not sufficiently distinct from the underlying siltstone and has restricted distribution.

The lower part of the Holmwood Shale comprises grey-green shale, and the upper portion is mainly grey to black clayey siltstone. Rare erratic boulders deposited by melting icebergs are often present within the basal portion (Le Blanc Smith & Mory 1995; Mory 1995b). Thin, brown, clayey limestone beds of the Beckett Member are present within the lower shaley portion of the formation. The upper clayey siltstone portion is well bedded with mica, jarosite (potassium and iron hydrous sulfate that is probably an oxidation product of pyrite) and gypsum (Le Blanc Smith & Mory 1995).

At the top of the Holmwood Shale, the Fossil Cliff Member is a mainly bioclastic calcarenite forming thin, lenticular beds within siltstone and shale becoming sandier in the east towards the Darling Fault (Le Blanc Smith & Mory 1995). A lower conspicuous fossiliferous limestone section, defined as the Woolaga Creek Limestone Member by Playford (1959), has been observed in the Woolaga Creek area near the Darling Fault east of Mingenew, but it has not been observed elsewhere.

Sandstone units are present in the upper formation in its north-eastern areas (Johnstone & Willmott 1966). These were intersected in petroleum wells Abbarwardoo 1 (279–333 m and 387–429 m), Wicherina 1 (953–1003 m) and Depot Hill 1 (1885–1920 m), and described in Abbarwardoo 1 (Burdett 1963) as a mainly fine-grained, friable quartz sand with minor clay matrix; however, this unit is coarse to very coarse grained in wells further to the south.

Downhole gamma-ray logs over the Holmwood Shale display a characteristically high gamma-ray count across the shale and clayey siltstone with low count associated with sandstone units (Figure 20, Figure 21 and Figure 22). In outcrop, the Holmwood Shale weathers to a white, yellow and pale to medium brown colour, and can appear very similar to weathered Nangetty Formation (Hocking et al. 1982; Le Blanc Smith & Mory 1995).

The Holmwood Shale was deposited in a cold-water marine environment under mainly reducing conditions, interpreted from the lack of benthic fauna (Playford et al. 1976). Rare, erratic boulders indicate occasional deposition from icebergs (Playford et al. 1976), and intervals of fossiliferous limestone suggest periods of well-aerated conditions that allowed benthic fauna to flourish (Playford et al. 1976). Palynological assemblages include some plant microfossils (Segroves 1971) and microfossils include mainly foraminifera (Crespin 1958) in shale. Most macrofossils are confined to the limestone beds, including pelecypods, gastropods, brachiopods, nautiloids, ostracods, coral, bryozoans and the ammonoid *Juresanites jacksoni* (Playford et al. 1976). The Fossil Cliff Member has a particularly abundant and large variety of benthic fauna fossils (Playford et al. 1976; Baxter & Lipple 1985). The formation lies mostly in the *Pseudoreticulatispora* confluence palynological zone, while at the top of the formation the Fossil Cliff Member belongs to the *P. pseudoreticulata* Zone, indicating an Asselian to Sakmarian age in the Early Permian (Backhouse 1993a).

The Holmwood Shale outcrops on the Irwin Terrace within watercourses. The main outcrops are in the Irwin and Lockier rivers (Playford et al. 1976, Mory & Iasky 1996). The northernmost outcrops are likely in the Murchison River valley, 13–25 km south of Bompas

Hill (Playford et al. 1976). The formation is found at considerable depth under most of the northern portion of the northern Perth Basin, including the Dandaragan Trough, the Cadda Terrace and the Beagle Ridge (Playford et al. 1976, Mory & Iasky 1996). It extends as far south as the petroleum well Cadda 1 and northward onto the Coolcalalaya Terrace (van de Graaff et al. 1980).

Like the Nangetty Formation, the Holmwood Shale is thickest in the east upon the Irwin Terrace (Mory & Iasky 1996), where it is between 400 and 700 m thick (Le Blanc Smith & Mory 1995). It thins westward across the Allanooka High. The type section of the formation is 566 m but, due to repetition from faulting, the true thickness might be closer to 450 m (Playford & Willmott *in* McWhae et al. 1958; Playford et al. 1976). Upon the eastern margin of the Allanooka Terrace, petroleum well Depot Hill 1 intersected 625 m of the Holmwood Shale (Mory 1995b). The Fossil Cliff Member has a maximum known thickness of 47.5 m at Beckett Gully (Muhling & Low 1977).

The Holmwood Shale was deposited conformably upon the Nangetty Formation, and is overlain with an apparent conformity by the High Cliff Sandstone (Le Blanc Smith & Mory 1995). On the Beagle Ridge and Greenough Shelf, the Holmwood Shale unconformably overlies basement rocks (Mory & Iasky 1996). The formation is equivalent to the Moorhead Formation in the Collie Basin (Le Blanc Smith & Mory 1995), and the Carrandibby and Callytharra formations of the Carnarvon Basin (van de Graaff et al. 1980).

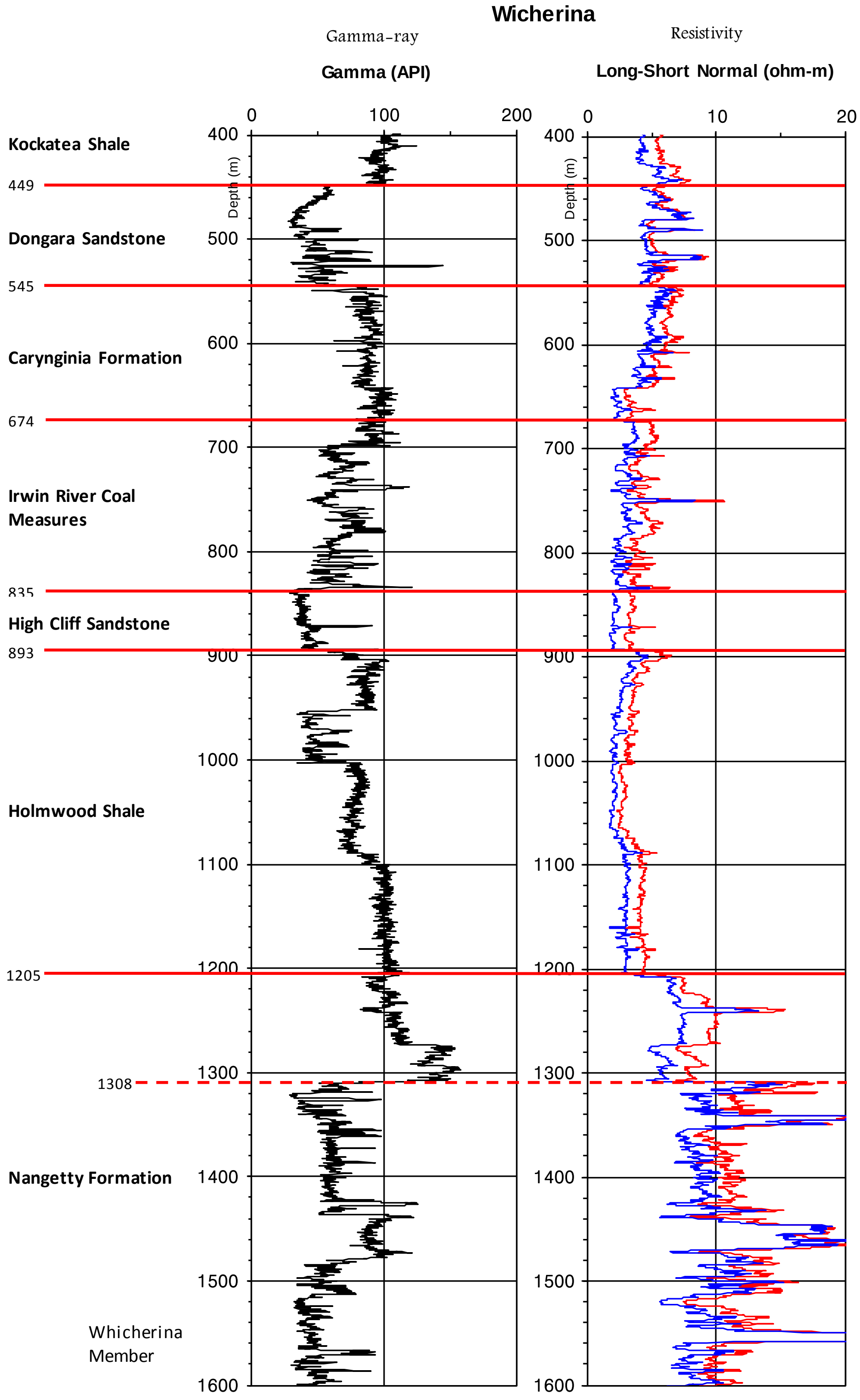

Figure 20 Downhole geophysical log from petroleum well Wicherina 1 (400–1600 m bgl) showing Permian formations

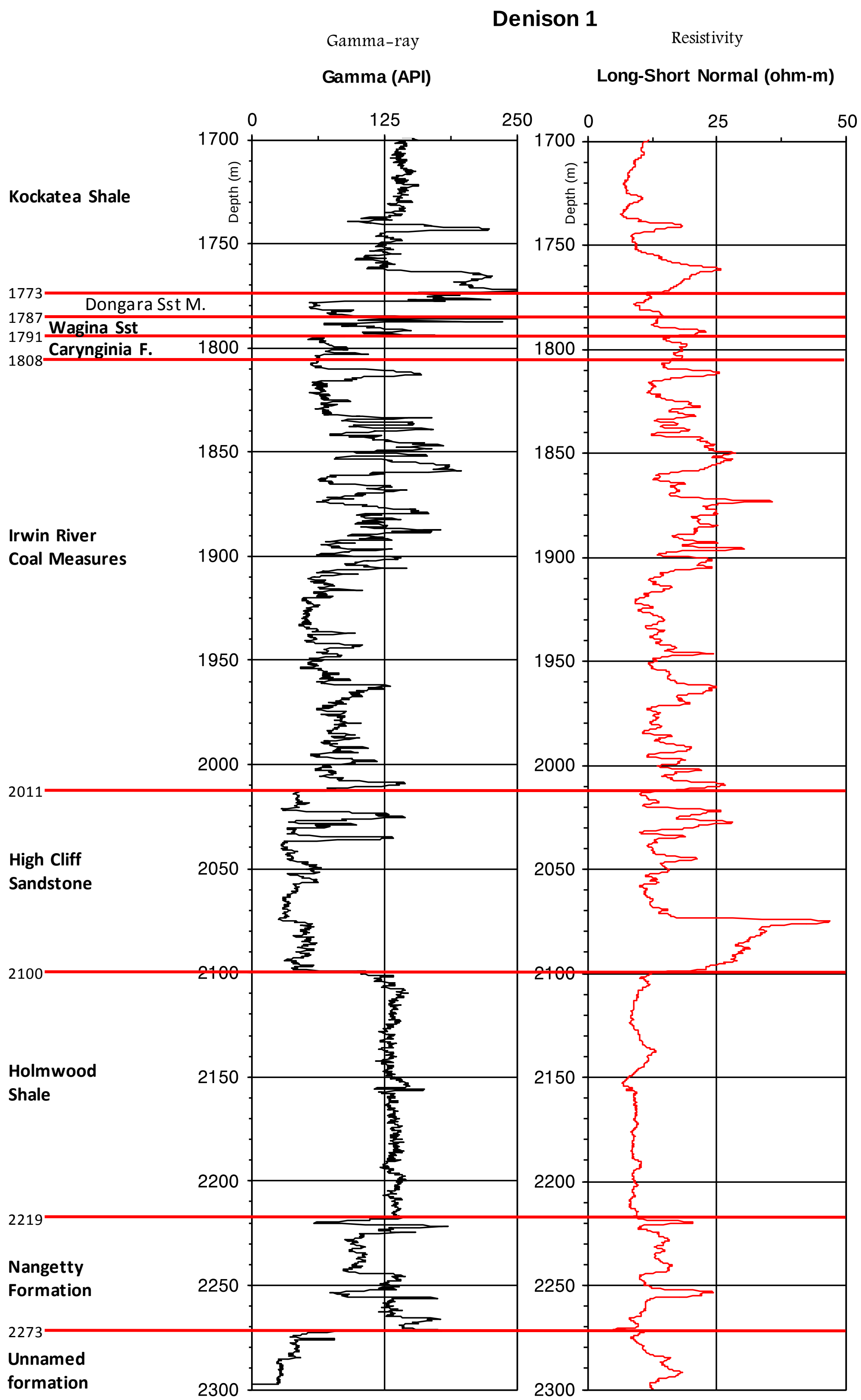

Figure 21 Downhole geophysical log from petroleum well Denison 1 (1700–2300 m bgl) showing the Permian formations

4.6 High Cliff Sandstone

The High Cliff Sandstone was introduced by Clarke et al. (1951) to represent an Early Permian sequence of interbedded sandstone, conglomerate and minor siltstone. The type section is located at High Cliff, on the south bank of the Irwin River north branch (MGA Zone 50, 358419 m E, 6797439 m N) on the Irwin Terrace where the formation is 26 m thick (Le Blanc Smith & Mory 1995). Outcrops of the High Cliff Sandstone are restricted to the Irwin Terrace, with the main exposures in the Irwin and Lockier rivers area. In exposure, the formation consists of a broadly upward-coarsening section of highly bioturbated, rippled, silty sandstone.

It has been suggested that the High Cliff Sandstone be redefined as a member unit of the Irwin River Coal Measures, as the contact can be gradational and the units difficult to distinguish (Le Blanc Smith & Mory 1995; Mory & Iasky 1996).

The High Cliff Sandstone comprises upward coarsening, white to medium grey, highly bioturbated, fine- to medium-grained silty sandstone, to coarse and very coarse grained sandstone and gravel. The coarse-grained sandstone is cross-bedded with thin pebble conglomerate beds (Le Blanc Smith & Mory 1995). The grain size of the sandstone appears to coarsen towards the Darling Fault, and possibly also towards the Urella Fault (Playford et al. 1976). Towards the base, the formation is more argillaceous with minor, thin interbedded siltstones that are medium to dark grey and carbonaceous. This part includes some angular to subangular erratic boulders up to 60 cm in diameter (Le Blanc Smith & Mory 1995).

Downhole geophysical logs through the formation typically have a low gamma-ray count, but often show a gradational contact with the overlying Irwin River Coal Measures (Figure 20 and Figure 21). Le Blanc Smith and Mory (1995) noted it can be difficult to distinguish the High Cliff Sandstone from the Irwin River Coal Measures in bores where the High Cliff Sandstone is thin and contains a similar proportion of siltstone to the overlying Irwin Coal Measures.

The High Cliff Sandstone was probably deposited in a delta front environment with shallow marine, lower deltaic and beach ridge elements (Playford et al. 1976; Baxter & Lipple 1985; Mory 1995b; Mory & Iasky 1996). This interpretation is supported by cross-stratification, wave ripples, sporadic conglomerate lenses, rippled siltstone drapes, and some marine fossils (Le Blanc Smith & Mory 1995). Erratic boulders suggest a proglacial setting (Le Blanc Smith & Mory 1995).

The depositional centre for the High Cliff Sandstone appears to be located on the Allanooka Terrace and Bookara Shelf (Mory & Iasky 1996), and it is thickest upon the Allanooka Terrace, where the maximum intersection of 150 m was in Mount Horner 1 (Mory & Iasky 1996). On the Irwin Terrace, the High Cliff Sandstone thickens from 26 m at the type section to 42 m to the south at Woolaga Creek (Playford et al. 1976). The formation thins to the west onto the Greenough Shelf and Dongara Terrace.

Normally the High Cliff Sandstone is unfossiliferous (Le Blanc Smith & Mory 1995; Mory & Iasky 1996). However, there is a marine fauna assemblage described at the base of the formation at Woolaga Creek that includes bivalves, gastropods and brachiopods, indicating an Artinskian age (Playford et al. 1976; Baxter & Lipple 1985). Although palynofloras have not been found in the sandstone, Backhouse (1993a) estimates that the High Cliff Sandstone is probably within the Artinskian *Striatopodocarpites fusus* Zone.

As with the other underlying Permian formations, the High Cliff Sandstone is present across the northern Perth Basin, extending from the Irwin Terrace west to the Greenough Shelf and Beagle Ridge. It also extends north, where it is recognised on the Coolcalalaya Terrace (van de Graaff et al. 1980) and is probably present at depth within the Dandaragan Trough. The formation is correlated with the Westralia Sandstone in the Collie Basin, and other units in the Wilga, Boyup and Southern Perth Basin (Le Blanc Smith 1993). There is a conformable, sharp contact between the High Cliff Sandstone and the underlying Holmwood Shale, while the contact with the overlying Irwin River Coal Measures is conformable and typically transitional.

4.7 Irwin River Coal Measures

The Irwin River Coal Measures were introduced by Clarke et al. (1951) as a coal bearing sequence of sandstone, siltstone and shale between the High Cliff Sandstone and the Carynginia Formation. The type section is located along the north branch of the Irwin River, from about 500 m upstream from High Cliff (MGA Zone 50, 358419 m E, 6797439 m N), where it is 55 m thick (Playford et al.,1976). The Irwin River Coal Measures consist of alternating beds of sandstone, siltstone with carbonaceous shale, coal seams and infrequent conglomerate and limestone (Le Blanc Smith & Mory 1995, Mory 1995b, Muhling & Low 1977). The sandstones are often strongly cross-bedded, with some current ripple marks, and are coloured white, red, yellow or brown (Playford et al. 1976). Le Blanc Smith (1993) correlated the Irwin River Coal Measures with the Ewington Coal Measures of the Collie Basin, and it can also be correlated with the Keogh and Billidee formations of the Carnarvon Basin, and even the Vryheid Formation in the Karoo Basin of southern Africa (Le Blanc Smith & Mory 1995).

The upper portion of the formation is dominated by siltstone and claystone with subordinate sandstone and minor coal. It is light to medium grey, and dark grey over the carbonaceous intervals. The siltstone is micaceous, and carbonised wood fragments are common within the claystone. Sandstone within the upper portion is mostly fine grained, and is massively bedded with common small-scale current bedding and slump structures (Playford et al. 1976). In parts, the sandstone is calcareous, grading into a sandy limestone.

The lower portion of the Irwin River Coal Measures is dominated by sandstone with interbedded siltstone and minor shale. The sandstone is white, light to medium grey, fine and coarse to very coarse grained, moderately sorted, kaolinitic, carbonaceous, micaceous and pyritic. Pebbles are often present within the coarse-grained sandstone, which sometimes grades into conglomerate lenses. The coarse-grained sandstone is typically poorly consolidated, while the fine-grained sandstone often has an argillaceous matrix and moderately to well-developed siliceous cementation. Cross-bedding and ripples are abundant in the sandstone, with wavy and flat lamination, rootlets and bioturbation (Le Blanc Smith & Mory 1995). A number of thin, lenticular, sub-bituminous coal seams are present within the lower part of the formation.

Downhole geophysical logs of the Irwin River Coal Measures typically show an irregular gamma-ray pattern with short intervals of high and low counts, normally containing one or two thicker intervals of low gamma-ray count corresponding to sandstone-dominated sections (Figure 20 and Figure 21).

The Irwin River Coal Measures were probably deposited on a lower delta plain formed from a series of coalesced alluvial deltas. This interpretation is supported by the lack of marine fossils and lenticular bedding (Le Blanc Smith & Mory 1995), and the presence of herbaceous flora (McLoughlin 1991). The upper portion of the formation grades into the overlying marine Carynginia Formation, coincident with a progressing cold-temperature, marginal marine embayment and fore-beach environment (Playford et al. 1976; Le Blanc Smith & Mory 1995).

Coalified plant remains, rootlets and bioturbation indicate an active faunal and floral presence (Mory & Iasky 1996). Palynological assemblages belong to the *Microbaculispora trisina* palynostratigraphic zone, with the *Striatopodocarpites fusus* Zone within the lower portion of formation (Backhouse 1993a) indicating an Artinskian (Early Permian) age. It is rich in the Permian flora *Glossopteris* (Rigby 1966) and contains abundant spores and pollen (Segroves 1969, 1970, 1971).

The Irwin River Coal Measures outcrop on the Irwin Terrace from the Greenough River to Woolaga Creek. In the subsurface, the Irwin River Coal Measures occur throughout much of the northern Perth Basin and thicken westward from the Irwin Terrace into a depositional centre probably across a broad north–south depression located over the western part of the Allanooka High and possibly extending into the Dandaragan Trough (Mory & Iasky 1996). The formation thins west onto the Beagle Ridge, while on the Greenough Shelf it has been eroded during a middle Permian erosion event so that the full sequence is not preserved (Mory & Iasky 1996). The maximum thickness of Irwin River Coal Measures intersected was 307 m in Arrowsmith 1 (Mory & Iasky 1996).

The Irwin River Coal Measures lie conformably between the High Cliff Sandstone and the Carynginia Formation. The lower boundary is defined as the lowest carbonaceous to coaly shale or siltstone overlying medium- to coarse-grained sandstone of the High Cliff Sandstone (Playford et al. 1976; Le Blanc Smith and Mory 1995). The upper boundary is at the base of the jarositic micaceous siltstone that is characteristic of the Carynginia Formation (Playford et al. 1976).

4.8 Carynginia Formation (including Mingenew Formation)

The Carynginia Formation is an Early Permian siltstone, claystone and sandstone sequence between the Irwin River Coal Measures and overlying Wagina Sandstone, Dongara Sandstone and Beekeeper Formation (Clarke et al. 1951; Playford & Willmott *in* McWhae et al. 1958). Carynginia Gully is the type locality, although the formation is discontinuous in this area. Playford and Willmott (1958) subsequently selected an exposure along Woolaga Creek as the main reference section (MGA Zone 50, 369692 m E, 6770482 m N).

The Carynginia Formation is similar to the Holmwood Shale and consists of black, grey and brown micaceous siltstone and claystone with grey to dark brown quartz sandstone containing thin, fine conglomerate beds (Le Blanc Smith & Mory 1995; Muhling & Low 1977; Mory 1995b). Within the formation, there are common yellow patches and layers of jarositic siltstone. The sandstone is predominantly fine to medium grained, forming lenticular beds with internal cross-laminae. Portions of sandstone have been reworked by wave and storm action leaving ripple and cross-stratification structures, and the sandstone content increases in the south and east (Le Blanc Smith & Mory 1995). In the lower portion of the formation there are boulder sized erratics of granitoid, gneiss and quartzite, attributed to proglacial ice-rafting processes (Playford et al. 1976). Descriptions from petroleum wells often identify four units comprising varying portions of claystone, siltstone and sandstone, commencing with a basal siltstone and claystone with minor sandstone.

Downhole geophysical logs through the Carynginia Formation show a relatively uniform and high gamma-ray count, with minor intervals of slightly low gamma-ray count possibly related to the presence of sandstone (Figure 20 and Figure 21).

The Carynginia Formation was deposited in a cold, shallow marine environment as indicated by the trace-fossil assemblages, common bioturbation, cross-stratification, wave ripples and conglomeratic lenses (Backhouse 1993). Glacial dropstones in the lower part of the formation suggest that icebergs dropped material onto the sea floor during the early stages of deposition. The increasing frequency of spinose acritarchs through the upper part of the formation indicates that open marine conditions became more prevalent in the later phase of deposition (Backhouse 1993). Spores and pollen are common in the Carynginia Formation (Segroves 1969, 1970, 1971), and are more prevalent than foraminifera (Crespin 1958). Backhouse (1993) recognised palynofloras from the *Praecolpatites sinuosus* Zone suggesting the Carynginia Formation is at Early Permian Artinskian age (Segroves 1971; Backhouse 1993b).

Outcrops of the Carynginia Formation are present across the Irwin Terrace, with the best exposures in the Irwin River and Woolaga Creek valleys. The formation extends at depth through most of the northern Perth Basin in the subsurface. At the reference section along Woolaga Creek, the formation is 236 m thick (Le Blanc Smith & Mory 1995). The formation thickens to the south, reaching a maximum of 337 m in well Erregulla 1 (Mory 1995b).

The contact between the Carynginia Formation and the underlying Irwin River Coal Measures is transitional and conformable. The upper contact with the overlying Wagina Sandstone, Dongara Sandstone or Beekeeper Formation is an angular unconformity (Playford et al. 1976; Mory & Iasky 1996).

The Carynginia Formation is correlated with the Allanson Sandstone and lower Premier Coal Measures in the Collie Basin (Le Blanc Smith 1993), and with the Byro Group in the Carnarvon Basin (Le Blanc Smith & Mory 1995).

A unit described as the Mingenew Formation along the Urella Fault System appears to be a local sandy, fossiliferous variation of the Carynginia Formation (Playford et al. 1976; Archbold 1988).

4.9 Wagina Sandstone, Dongara Sandstone and Beekeeper Formation

The Wagina Sandstone, Dongara Sandstone and Beekeeper Formation are the uppermost Permian formations recognised within the northern Perth Basin. They represent various facies of a deltaic system (Mory & Iasky 1996; Laker 2000). There is a facies change from the fluvial and deltaic plain deposits of the Wagina Sandstone, to the bioturbated delta front marine sands of the Dongara Sandstone, and the distal deltaic marine sequence of sandstone and limestone of the Beekeeper Formation (Mory 1995b, Mory & Iasky 1996). Late Permian palynoflora suggest that they are partly equivalent where the Wagina Sandstone interfingers with the Dongara Sandstone to the west, and further interfingers with the Beekeeper Formation to the south-west (Mory & Iasky 1996).

Laker (2000) suggests that these formations are diagenetically related, and should be grouped together as the Wagina Formation with two members: the Wagina Sandstone and Dongara Sandstone. As such, the terms Wagina and Dongara used by Laker (2000) refer to different portions of the succession than those used by Mory and Iasky (1996). The Wagina Sandstone Member of Laker (2000) largely corresponds to the Beekeeper Formation of Mory and Iasky (1996). The terminology used by Mory and Iasky (1996) is followed in this publication.

Wagina Sandstone

The Wagina Sandstone was named by Clarke et al. (1951) based on a type section at Wagina Well in the south branch of the Irwin River; however, exposures near the type section are limited. Playford and Willmott (*in* McWhae et al. 1958) proposed that the main reference section for the unit is near Woolaga Creek (MGA Zone 50, 370496 m E, 6771075 m N), Red Hill to near the Darling Fault. Mory and Iasky (1996) restricted the Wagina Sandstone to outcrops along the eastern part of the Irwin Terrace and northern Allanooka High, as to exclude the Dongara Sandstone.

The Wagina Sandstone consists mainly of white to medium grey, clayey sandstone, which is predominantly fine to medium grained with medium- to coarse-grained intervals, and minor beds of siltstone, claystone and low-grade coal (Playford et al. 1976; McTavish 1964; Mory & Iasky 1996; Laker 2000). The sand is angular to subrounded, poorly to well sorted and friable, and includes pebbly sandstone and lesser conglomerate beds (McTavish 1964; Gorter et al. 1984). Upward-fining cross-bedded sequences are present in the sand (Mory & Iasky 1996; Laker 2000). The siltstone is soft to firm, off-white, light grey and greenish, and micaceous, while the claystone is off-white to dark grey to black, slightly to moderately carbonaceous (Gorter et al. 1984).

Downhole gamma-ray logs have a low gamma-ray count with some peaks associated with clay and siltstone layers (Figure 21).

The Wagina Sandstone was deposited in a foreshore or delta (proximal delta front or delta top) setting with fluvial and tidal influences (Laker 2000). The coarse-grained sands were deposited by braided streams and sheet flow (Bergmark & Evans 1987). The interbedded siltstone and coal is associated with floodplain and swamp deposits over a delta plain (Le Blanc Smith & Mory 1995; Laker 2000).

Palynofloras encountered in the Wagina Sandstone include *Dulhuntyispora parvithola*, *Camptotriletes warchianus, Microreticulatisporites bitriangulatus, Verrucosisporites* sp. cf. *V. trisecatus and Triadispora* sp. cf. *T. epigona* (Mory & Iasky 1996). These are attributed to the *Microbaculispora* sp*.* A zone, indicating that the Wagina Sandstone is Late Permian (Playford et al. 1976; Le Blanc Smith & Mory 1995), possibly of Changhsingian age. Acritarch palynoflora and plant macrofossils are also present within the Wagina Sandstone (Mory & Iasky 1996). The formation correlates with the upper part of the Sue Coal Measures in the southern Perth Basin.

Deposition of the Wagina Sandstone took place in an alluvial fan delta centred at the Darling Fault (Bergmark & Evans 1987). On the Irwin Terrace, coal-forming swamps developed on the flanks of the main fan. West of the Urella Fault, the Wagina Sandstone interfingers and grades into the Dongara Sandstone. Outcrops are present at several locations adjacent to the Darling Fault about the Lockier and Irwin rivers, and along the Greenough River at Wicherina. A thickness of 243 m is estimated on the Irwin Terrace near the Woolaga Creek (Le Blanc Smith & Mory 1995) but might be thicker where it is truncated (Muhling & Low 1977; Le Blanc Smith & Mory 1995). Upon the Irwin Terrace, the Wagina Sandstone rests upon the Carynginia Formation with a low-angle unconformity (Mory & Iasky 1996) and its upper surface is truncated and overlain by a veneer of Cenozoic sediments. It is disconformably overlain by the Kockatea Shale near the Greenough River.

Dongara Sandstone

The Dongara Sandstone is a clean, bioturbated silty sandstone underlying the Kockatea Shale (Mory & Iasky 1996). The type section is in Dongara No. 11 (MGA Zone 50, 306686 m E, 6760842 m N) at depths of between 1682 and 1713 m (Mory & Iasky 1996). The upper portion was previously referred to as the ‘Basal Triassic Sandstone’ by Hosemann (1971), and in the Yardarino–Dongara area was attributed to the Yardarino Sandstone Member (Playford et al. 1976) for the upper 60 m of quartz sandstone.

The Dongara Sandstone is a marine sand comprising white to grey, friable, bioturbated medium- to coarse-grained sandstone with minor pebble bands, conglomerate, carbonaceous siltstone and shale. The sand is angular to subrounded but mostly subangular, moderately to well sorted, and can contain minor pyrite. Fine-grained intervals can have silica cementation with a trace of calcareous cementation (Discovery Petroleum 1995a). The sandstone has upward-coarsening sequences (Laker 2000). The upper portion has less clay and is coarser grained, with less bioturbation (Mory & Iasky 1996), and contains a significant portion of monazite (Rasmussen et al. 1989). Thin interbeds of limestone can be present near the base of the formation and towards its southern limit (Mory & Iasky 1996), suggesting that the unit interfingers with the Beekeeper Formation to the south.

Gamma-ray logs through the Dongara Sandstone show a low gamma-ray count associated with the sand lithology, with increases in gamma-ray count across siltstone and shale intervals (Figure 20 and Figure 21). The upper sand of the Dongara Sandstone is particularly pure with a consistently low gamma-ray count, resulting in a marked contrast between this sand and the high gamma-ray count of the overlying Kockatea Shale.

The Dongara Sandstone is a proximal fan to delta front deposit laid down during deltaic propagation (Mory & Iasky 1996; Laker 2000). The fluvial beach and littoral environments of the Dongara Sandstone transition into the marginal marine and shallow marine environments of the Beekeeper Formation (Tupper et al. 1994). The Dongara Sandstone contains palynofloras from the *Dulhuntyispora parvithola*, *D. dulhuntyi* and *D. ericians* zones (Backhouse 1992b), indicating that it was deposited in the Late Permian; however, it might extend into the earliest Triassic (Playford et al. 1976; Mory 1995b).

The Dongara Sandstone is located west of the Urella Fault, between the Wagina Sandstone on the Irwin Terrace and the Beekeeper Formation over the Beagle Ridge. It reaches a maximum thickness of 336 m in petroleum well Depot Hill 1, about 9 km west of the Urella Fault and decreases towards the south-west (Mory & Iasky 1996). The formation is less than 60 m thick in the Dongara gasfield and 31 m thick in petroleum well Dongara 11. The formation disconformably overlies the Carynginia Formation and is overlain by the Kockatea Shale, although it is uncertain whether this contact is conformable or disconformable (Mory 1995b; Mory & Iasky 1996). There is a gradual and often interfingering transition to the Beekeeper Formation to the south-west (Mory & Iasky 1996), and probably a similar contact with the Wagina Sandstone to the east.

Beekeeper Formation

The Beekeeper Formation was defined by Hall and Kneale (1992). It was previously recognised informally by Lane and Watson (1985) as the Carynginia Limestone and was subsequently incorporated as part of the 'Wagina Formation' by Tupper et al. (1994). It has also been named the Wagina Sandstone Member by Laker (2000). GSWA recognise it as a separate formation, with a type section for the Beekeeper Formation given as between 2239 and 2353 m depth in petroleum well Woodada No. 1 (MGA Zone 50, 320458 m E, 6702620 m N) (Hall & Kneale 1992).

The Beekeeper Formation consists of fine- to medium-grained sandstone with upward-fining sequences (Laker 2000) or medium- to coarse-grained sandstone (Mory & Iasky 1996), with intercalated beds of limestone, calcareous sandstone and mudstone/shale. In the north, the formation mainly consists of sandstone and dark grey mudstone, but limestone is dominant in the south (Mory & Iasky 1996; Laker 2000).

Gamma-ray logs through the Beekeeper Formation have a low to very low count associated with the sand and limestone lithologies. The Beekeeper Formation is distinguished from the Dongara Sandstone by the lack of peaks, which are observed across siltstone and shale intervals in the Dongara Sandstone. There is a marked contrast between the Beekeeper Formation and the high gamma-ray count of the overlying Kockatea Shale and the underlying Carynginia Formation.

The high portion of fossiliferous carbonate and abundant acritarchs indicate that an open marine depositional environment (Mory & Iasky 1996) developed at the distal margin of the delta system towards the offshore clastic shelf and delta front (Lane & Watson 1985; Laker 2000).

The limestone contains abundant macrofauna, including bryozoans, crinoids, brachiopods, bivalves and serpulids (Mory & Iasky 1996). The presence of *Dulhuntyspora* microflora suggests a late Wuchiapingian age (formerly Kazanian age), but might extend to the early Wuchiapingian of the Late Permian (Backhouse 1994).

The Beekeeper Formation does not outcrop but is widespread in the subsurface across the north-western part of the basin. It lies mostly upon the Beharra Springs Terrace and over the Beagle Ridge and Cadda Terrace, between Dongara and Cervantes. The most northern occurrence is in the Beharra Springs gasfield, about 30 km south-east of Dongara. The formation also extends south of Jurien Bay where it was intersected in petroleum well Cadda 1, 16 km east of the township (Crostella 1995). The Beekeeper Formation is 90 m thick in the Beharra Springs gasfield, increasing to a maximum intersected thickness of 134 m in petroleum well Point Louise No. 1 (Mory & Iasky 1996), about 10 km east of Green Head. The Beekeeper Formation lies disconformably on top of the Carynginia Formation (Mory & Iasky 1996) and underlies the Kockatea Shale, probably disconformably (Mory & Iasky 1996). It is partially coeval, and interfingers with the Dongara Sandstone to the north (Mory 1995b, Mory & Iasky 1996).

4.10 Kockatea Shale

The Kockatea Shale was first introduced by Playford and Willmott (*in* McWhae et al. 1958) based on a 12.5 m thick exposure near the Greenough River and Kockatea Creek junction (MGA Zone 50, 320897 E m, 6842040 m N) (Playford et al. 1970). The unit consists of light grey and greenish grey to black, micaceous shale, with minor siltstone and sandstone (Playford et al. 1976; Mory & Iasky 1996). In outcrop, the Kockatea Shale is bleached white or pale yellow, with red, purple and brown ferruginous beds and laminae. Distinct, lenticular sandstone and conglomerate beds are present in the lower part of the formation (Hosemann 1971; Playford et al. 1976).

Two sandy members are recognised in the Kockatea Shale within the northern portion of the basin: the Bookara Sandstone and Arranoo Members (Mory 1995b). The Bookara Sandstone Member is restricted to the northern portion of the basin within the lower Kockatea Shale (Mory & Iasky 1996). The Arranoo Member is a thinly bedded sandstone and siltstone sequence with minor limestone present in the upper portion of the Kockatea Shale in the Dongara – Mount Horner area (Mory 1995b). Mory and Iasky (1996) excluded the Dongara Sandstone (also known as ‘basal Triassic Sandstone’), which had been previously included as a member of the Kockatea Shale (Playford et al. 1976).

The Kockatea Shale was deposited under shallow marine conditions, as suggested by a rich and varied fossil marine flora and fauna assemblage, including bivalves, conodonts, and microplankton (Playford et al. 1976). The sandstone beds in the lower part of the formation might represent strandline accumulations or possible offshore bars (Hosemann 1971). The palynomorph assemblage in the unit ranges from the *Kraeuselisporites saeptatus* Zone (Dolby & Balme 1976) up to *Triplexisporites playfordii* Zone indicating a Scythian (Early Triassic) age (Mory & Iasky 1996).

The Kockatea Shale is readily identified in gamma-ray geophysical logs by a consistently high gamma-ray count, which contrasts with the overlying transitional Woodada Formation and the underlying Permian Dongara Sandstone or Irwin River Coal Measures (Figure 20 and Figure 21). However, the basal Bookara Sandstone Member of the Kockatea Shale has a distinctive low gamma-ray response, similar to the Dongara Sandstone (Figure 20, Figure 21 and Figure 22).

The Kockatea Shale is up to 1061 m in petroleum well Woolmulla No. 1 near Dongara. The thickness generally increases to the south, possibly reaching about 1200 m thick at petroleum well Cadda 1 near Jurien Bay (Mory 1994).

The Kockatea Shale is widespread throughout the northern Perth Basin, extending as subcrop beneath the superficial formations along the coast, from Wedge Island in the south to Leeman in the north (the southernmost recorded intersection was in Cataby Shallow CS23). It was intersected in subsurface east of the Urella Fault adjacent to the Darling Fault on the Yarra Yarra Terrace (Ellis 1983). It is also present at shallower depths over the Beagle Ridge, and the northern portion of the Perth Basin on the Greenough and Bookara Shelves. It was intersected at Bookara in Greenough Shallow bores 13, 14 and 15. The Kockatea Shale outcrops adjacent to and on top of the Northampton Inlier (Figure 18).

In the northern part of the basin, the Kockatea Shale overlies the Dongara Sandstone, possibly conformably (Mory & Iasky 1996); elsewhere, it rests unconformably on the Permian Carynginia Formation. Adjacent to the Northampton Inlier it unconformably overlies the Tumblagooda Sandstone, while west of Mount Hill it overlies Proterozoic metasediments (Mory & Iasky 1996; Playford et al. 1976). It is conformably overlain by the Woodada Formation through most of the basin; however, in the very north of the basin, it is disconformably overlain by the Cattamarra Coal Measures, Eneabba Formation or Lesueur Sandstone (Mory & Iasky 1996).

The Wittecarra Sandstone of the Carnarvon Basin possibly correlates with the Bookara Sandstone Member, or at a slightly higher level, near the base of the Kockatea Shale, north of Dongara (Hocking & Mory 2006). The Wittecarra Sandstone is disconformable on the Tumblagooda Sandstone, and consists of a basal conglomerate, overlain by silty sandstone and siltstone, sandstone, conglomerate, and capped by sandstone with probable plant rootlets.

4.11 Woodada Formation

The Woodada Formation is a Triassic sandstone and siltstone sequence (Willmott and McTavish, *in* Willmott 1964). Its type section is shown in stratigraphic well BMR 10 (MGA Zone 50, 304473 m E, 6698778 m N) between 334 m and 610 m. Willmott (1964) also provided a reference section for the Woodada Formation in petroleum well Woolmulla 1 between 1012 and 1231 m.

The Woodada Formation comprises fine-grained sandstones and interbedded siltstone. The sandstone is light grey, moderately sorted, thin-bedded and kaolinitic. The siltstones are dark grey, carbonaceous, micaceous and finely laminated. The prevalence of siltstone increases with depth as the unit grades into the underlying Kockatea Shale (Playford et al. 1976).

The Woodada Formation represents a regressive depositional phase between the marine Kockatea Shale and the continental Lesueur Sandstone (Willmott & McTavish *in* Willmott 1964). Plant microfossils suggest that the Woodada Formation is a paralic deposit (Playford et al. 1976).

Downhole gamma-ray logs are transitional between the higher gamma-ray count of the underlying Kockatea Shale and the low gamma-ray count of the overlying Lesueur Sandstone (Figure 23).

Backhouse (1992b) identified palynoflora from the *Triplexisporites playfordii* floral zone within the unit, indicating an Early to Middle Triassic age between the Olenekian and Anisian ages, which supports the previous palynological analyses by Balme (1969).

The Woodada Formation is widespread in the subsurface of the northern Perth Basin, extending from just north of Dongara to Jurien Bay (Playford et al. 1976). It thickens to the south, reaching about 230 m in the Woodada gasfield, with a maximum known thickness of 276 m at BMR 10 stratigraphic well, 13 km north of Leeman.

Over most of the northern Perth Basin, the Woodada Formation is conformably overlain by the Lesueur Sandstone and conformably overlies the Kockatea Shale (Playford et al. 1976). North of the Allanooka Fault, it is disconformably overlain by the Eneabba Formation or Cattamarra Coal Measures, whereas on the Beagle Ridge, the Woodada Formation subcrops the superficial formations in a narrow zone extending north-east of Leeman, and a small zone about 4 km east of Cervantes (Mory 1995a). The formation is disconformably overlain by the superficial formations in two bores (JB1 and JB11) near Jurien Bay (Harley 1974); although subsequent drilling indicates that these bores are more likely to have intersected Kockatea Shale and Lesueur Sandstone (Baddock & Lach 2003).

4.12 Lesueur Sandstone

The Lesueur Sandstone was named by Willmott et al. (1964) to denote a coarse-grained sandstone that outcrops at Mt Lesueur. The type section, as modified by Mory and Iasky (1996), is between 429 and 1012 m depth in petroleum well Woolmulla No. 1 (MGA Zone 50, 325726 m E, 6677130 m N), between Green Head and Eneabba.

The Lesueur Sandstone consists of pale brown to grey, fine to very coarse grained quartz sand and granules, which are poorly to moderately sorted, angular to subrounded, and cross-bedded. Intergranular, white kaolin clay is common, and is probably derived from weathered feldspar. Minor black heavy minerals, pyrite and carbonaceous material are present both as bands and scattered particles in the sandstone (Briese 1979b; Harley 1970). Minor layers of siltstone and conglomerate (Playford et al. 1976; Mory & Iasky 1996), with grey clay and thin black or grey micaceous shale become more frequent towards the base of the unit (Briese 1979; Harley 1970).

Deposition in a fluvial (Mory 1994) and possibly alluvial fan environment (Mory & Iasky 1996) is indicated by coarse-grained sediments, high-energy cross-bedding structures, and the absence of marine fossils.

Downhole gamma-ray logs typically show a low gamma-ray count for the sandstone, punctuated by discreet zones of high gamma-ray count corresponding to mudstone layers (lower 173 m of a 1202 m thickness shown in Figure 23), giving the unit a characteristic blocky gamma-ray profile (Mory & Iasky 1996). The transition to the underlying Woodada Formation is characterised by a consistently higher gamma-ray count.

In the northern Perth Basin, spores and pollen from the *Triplexisporites playfordii*, *Staurosaccites quadrifidus*, *Samaropollenites speciosus* and *Minutosaccus crenulatus–Ashmoripollis reducta* zones of Helby et al. (1987) are identified in the Lesueur Sandstone (Backhouse 1992b). These assemblages indicate an age of Anisian (Middle Triassic) to Norian (Late Triassic), and possibly Hettangian (Early Jurassic) (Mory 1994; Mory & Iasky 1996).

The Lesueur Sandstone is present over much of the Perth Basin, extending from just north of Dongara to the southern margin of the basin at the Southern Ocean, near Augusta. There is a small outcrop of Lesueur Sandstone outcrop in the Mt Lesueur area (not shown in Figure 24), west of the Lesueur Fault (Mory 1994a). It is present at shallow depth beneath the superficial formations mainly upon the Beagle Ridge between Leeman and Wedge islands (Figure 24). Eastward of the Beagle Ridge, the formation becomes progressively deeper. There is also a small area of Lesueur Sandstone mapped upon the Yarra Yarra Terrace, west of Coorow (Mory & Iasky 1996).

The Lesueur Sandstone conformably overlies the Woodada Formation and is conformably overlain by the Eneabba Formation (Mory 1994). The thickest intersection of Lesueur Sandstone was 1202 m within petroleum well Cadda 1, 17 km east of Jurien Bay, which encountered a complete section of the formation (Mory 1994). Watheroo Line WL 12 intersected 608 m of the Lesueur Sandstone 6 km east of Jurien Bay (Harley 1975), and Moora Line ML8A, 16 km south-east of Cervantes, penetrated 617 m of the formation without reaching the base (Briese 1979a). Near the northern margin of the Lesueur Sandstone near Dongara, the formation is only about 100 m thick (Mory & Iasky 1996). The formation thickens to the south and has been interpreted to be almost 3000 m thick in petroleum well Barberton 1 on the Barberton Terrace south of Moora (Mory & Iasky 1996). However, this interpretation might include Jurassic formations that could not be distinguished due to the low-grade palynology of the sediments.

4.13 Eneabba Formation

The Eneabba Formation is an Early Jurassic, multicoloured sandstone, siltstone and claystone unit. The type section is in petroleum well Eneabba 1 (MGA Zone 50, 338589 m E, 6727778 m N) between 2320 and 2978 m depth (Playford & Low 1972). The unit was informally referred to as the ‘Multicoloured Member’ of the Cockleshell Gully Formation by West Australian Petroleum Pty Ltd (WAPET) reports and was also known as the Eneabba Member of the Cockleshell Gully Formation (Playford & Low 1972). The Eneabba Member now has formational status (Mory 1994a), and the use of the name ‘Cockleshell Gully Formation’ has been discontinued (Table 9). The Greenough Sandstone of the Chapman Group described by Arkell and Playford (1954), which was intersected in the Geraldton area and onlapping the Northampton Inlier (Playford et al. 1976), has been incorporated into the Eneabba Formation. The names ‘Chapman Group’ and ‘Greenough Sandstone’ are no longer in use.

The Eneabba Formation consists of sandstone with interbedded siltstone and claystone. The sandstone is predominantly light grey to white and light green in parts. It is fine to very coarse grained, subangular to subrounded, moderately sorted and feldspathic. It is predominantly friable and weakly cemented by kaolin clay. The coarse sand grades into conglomerate in parts (Pudovskis 1962). The claystone is mottled and multicoloured red-brown, brown, yellow, pink, green, purple, grey and white with minor grey carbonaceous shale and thin coal seams.

The Eneabba Formation lies conformably between the Lesueur Sandstone and Cattamarra Coal Measures (Mory 1995). In the Geraldton area, it is locally disconformable on top of the Kockatea Shale and Proterozoic basement (Playford et al. 1976). Downhole geophysical logs show a spiky gamma-ray pattern due to more interbedded sandstone with siltstone and claystone compared to the overlying Cattamarra Coal Measures (Figure 25 and Figure 26).

Deposition was in a fluvial setting with meandering rivers (Mory 1995), while the multicoloured claystone suggest periods of exposure to oxidising conditions in a continental low-energy environment (Mory & Iasky 1996). Palynomorphs belong to the *Corollina torosa* Zone (Backhouse 1992a, 1993b), which is Early Jurassic, probably of Hettangian to Pliensbachian age. The base of the Eneabba Formation appears to be diachronous across the Triassic and Jurassic boundary south of Eneabba (Mory & Iasky 1996). The sediments frequently lack microfossils, which were presumably weathered in a continental environment (Mory & Iasky 1996). The only macrofossils are bivalves and rare fossil wood.

The Eneabba Formation is present at depth through most of the northern Perth Basin. The formation outcrops between the Lesueur and Peron faults north of Jurien Road, and west of the Lesueur Fault in the Mintaja and Eragilga Hills south of Jurien Road (Mory 1994a) and subcrops beneath the superficial formations to the north of Coolimba (Figure 18). The Eneabba Formation is absent on the Beagle Ridge south of Coolimba in the west, and on the Irwin Terrace in the east due to either erosion or a period of non-deposition during Early Jurassic (Mory & Iasky 1996).

The Eneabba Formation reaches a maximum recorded thickness of 854 m in petroleum well Donkey Creek 1.22 km north–northeast of Eneabba (Mory & Iasky 1996) and probably thickens further to the south, but has not been fully penetrated. The Eneabba Formation shallows towards the northern extent, and westward onto the Cadda Terrace, Beharra Springs Terrace and Dongara Terrace. The Eneabba Formation is present on the Yarra Yarra Terrace, where it was intersected in the Yarra Yarra Lakes monitoring bores west of Coorow and north of Lake Eganu (Yesertener 1999a). It extends as far inland as 20 km north-east of Geraldton, between the Hutt and Greenough rivers (based on previous descriptions of the ‘Greenough Sandstone’).

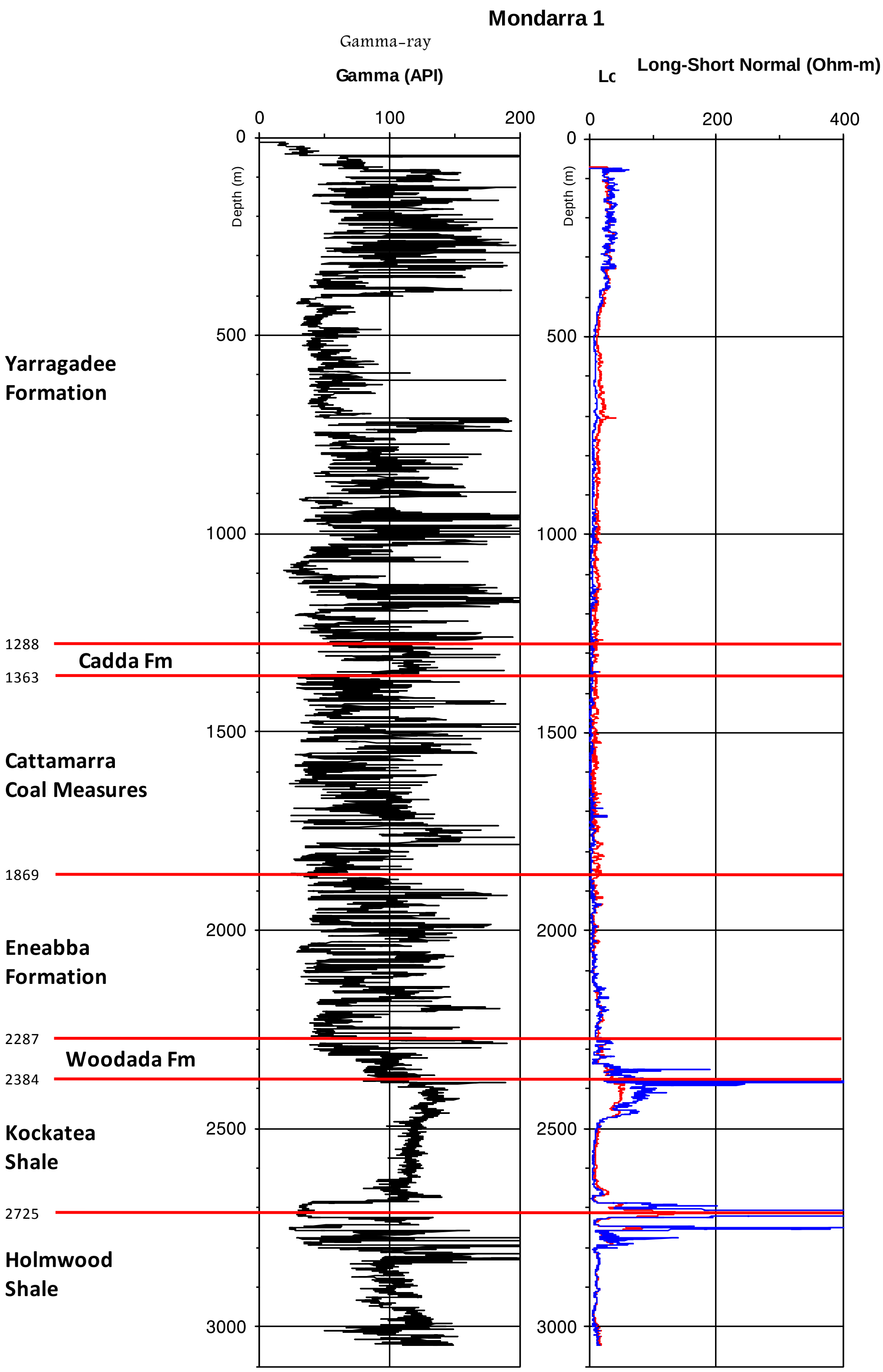

Figure 22 Downhole geophysical log from petroleum well Mondarra 1 (2384–2725 m bgl) showing the Kockatea Shale

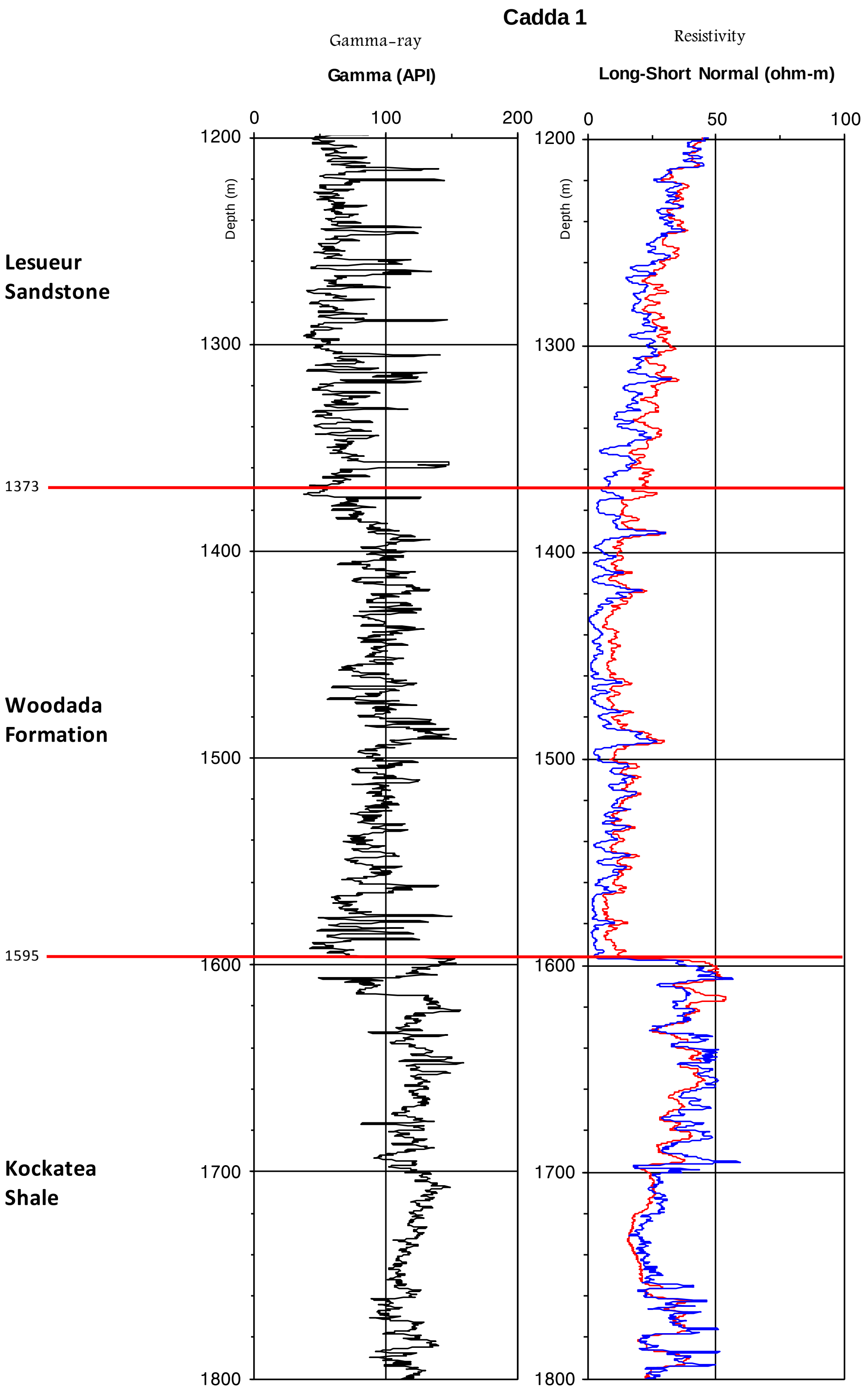

Figure 23 *Downhole geophysical log from petroleum well Cadda 1 (1200–1600 m bgl) showing the Woodada Formation*

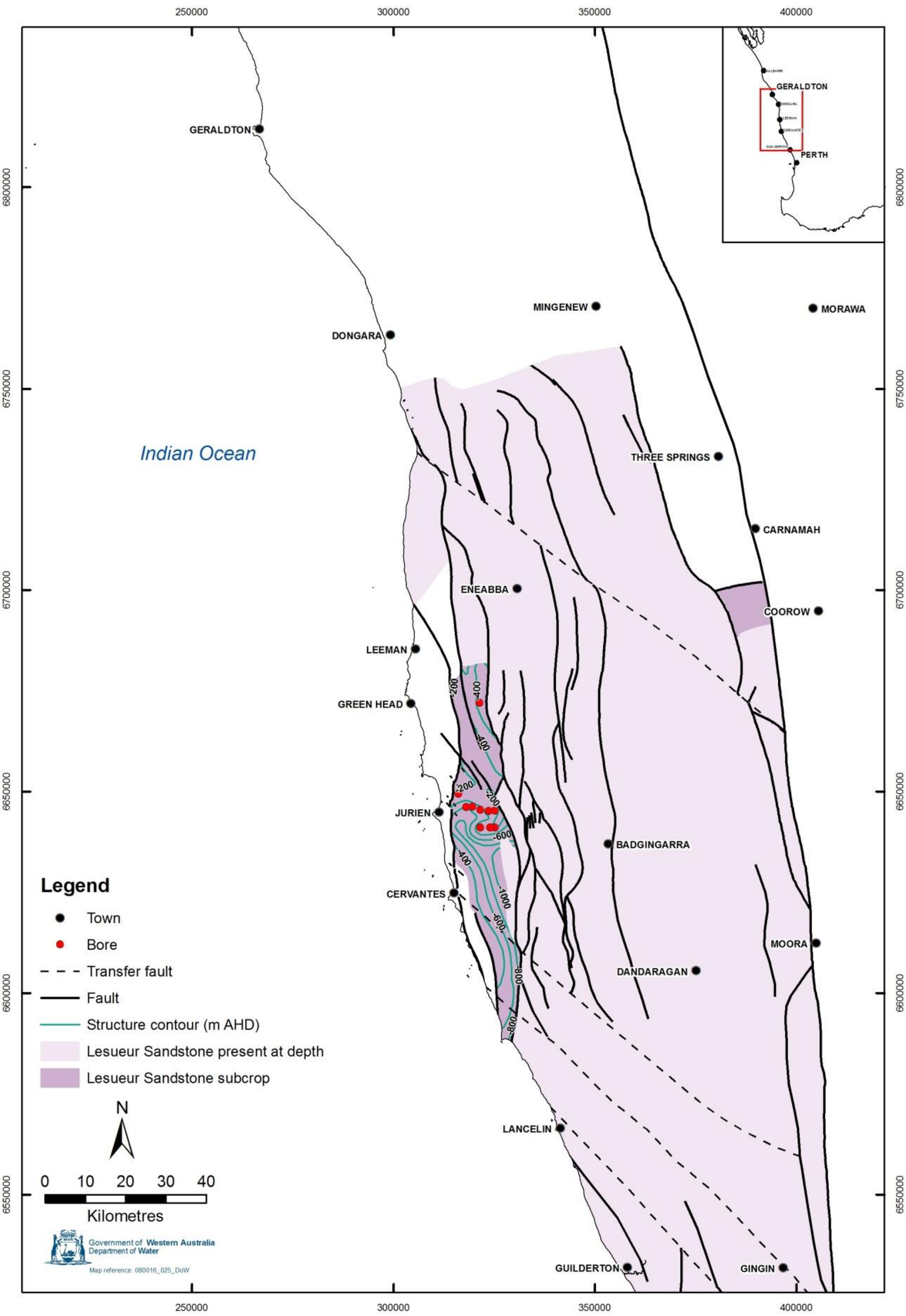

Figure 24 Lesueur Sandstone: contours on base of unit

Table 9 Nomenclature correlation for the Cadda Formation, Cattamarra Coal Measures and Eneabba Formation

<table>
<tr><th colspan="2">Overlying the Northampton Inlier</th><th colspan="2">Beagle Ridge</th><th>Dandaragan Trough</th></tr>
<tr><td colspan="2">Playford et al., 1976</td><td colspan="2">Playford et al., 1976</td><td>Mory & Iasky, 1994</td></tr>
<tr><td rowspan="4">Champion Bay Group</td><td>Kojarena Sandstone</td><td colspan="2" rowspan="4">Cadda Formation</td><td rowspan="4">Cadda Formation</td></tr>
<tr><td>Newmarracarra Limestone</td></tr>
<tr><td>Bringo Shale</td></tr>
<tr><td>Colalura Sandstone</td></tr>
<tr><td rowspan="2">Chapman Group</td><td>Moonyoonooka Sandstone</td><td rowspan="3">Cockleshell Gully Formation</td><td>Cattamarra Coal Measures Member</td><td>Cattamarra Coal Measures</td></tr>
<tr><td>Greenough Sandstone</td><td rowspan="2">Eneabba Member</td><td rowspan="2">Eneabba Formation</td></tr>
<tr><td colspan="2"></td></tr>
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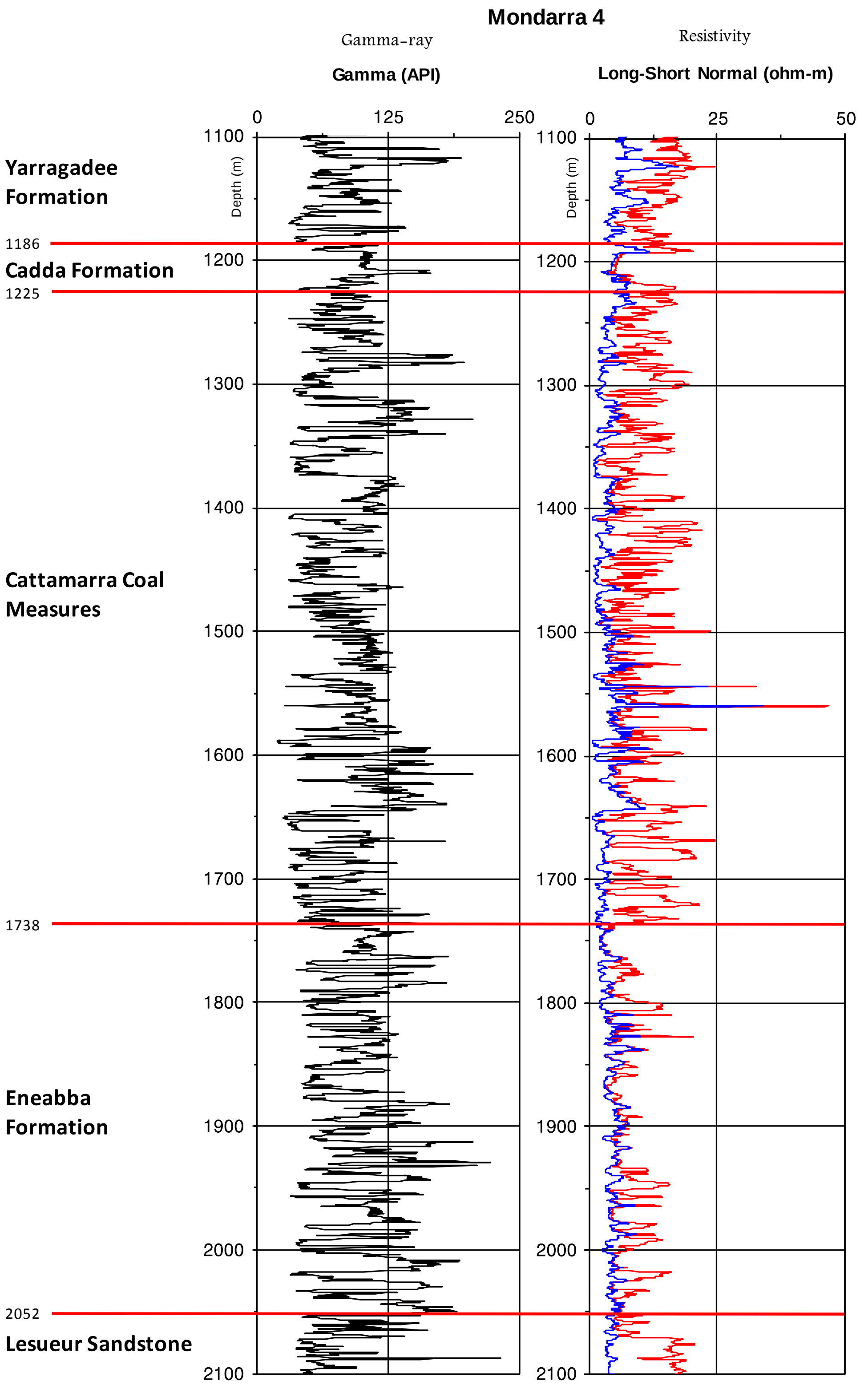


Figure 25 Downhole geophysical log from petroleum well Mondarra 4 (1200–2200 m bgl) showing the Cattamarra Coal Measures and Eneabba Formation

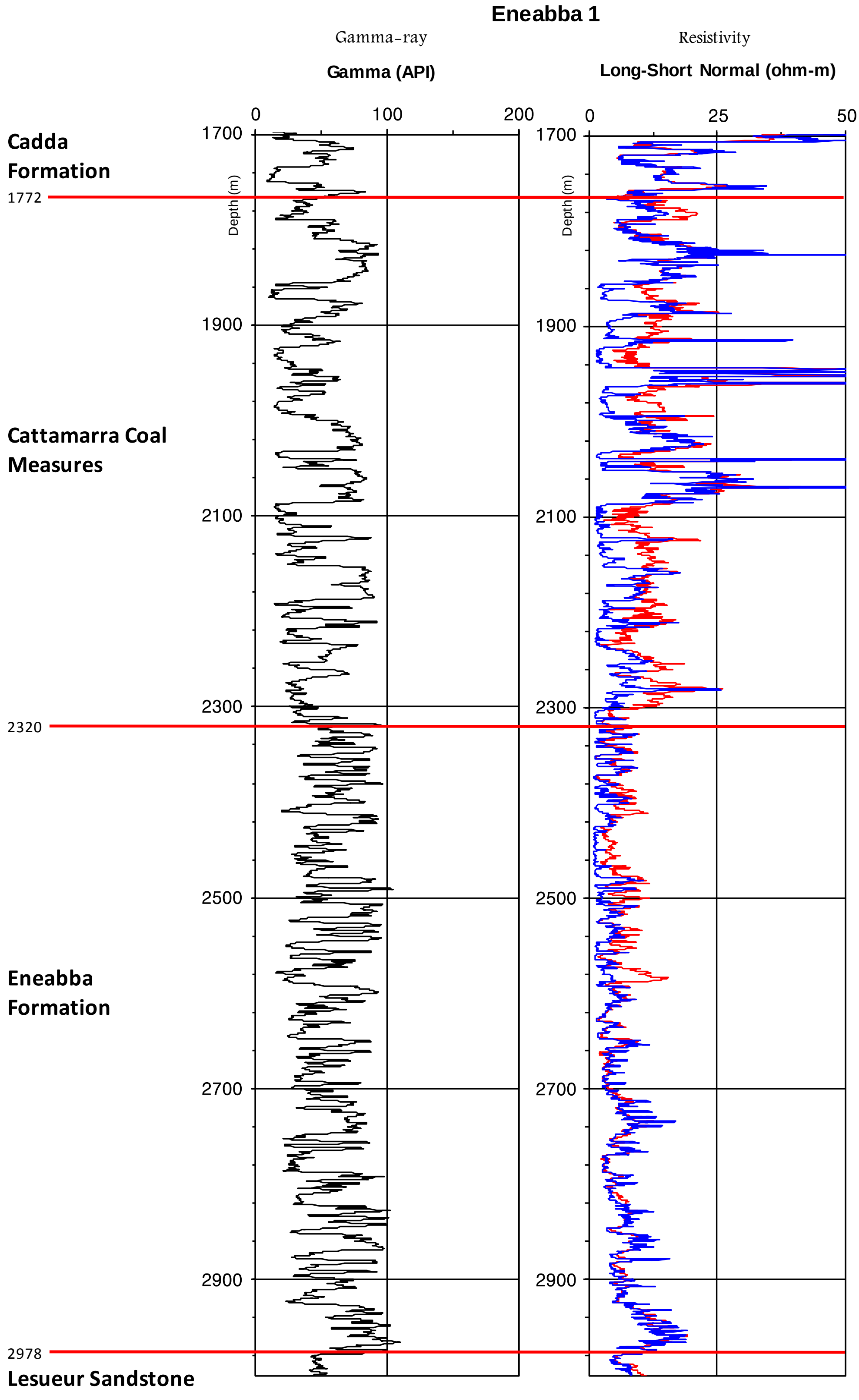


Figure 26 Downhole geophysical log from petroleum well Eneabba 1 (1700–3000 m bgl) showing the Cattamarra Coal Measures and Eneabba Formation

4.14 Cattamarra Coal Measures

The Cattamarra Coal Measures are Early Jurassic sandstones with dark carbonaceous siltstone and claystone interbeds, and coal seams. Playford and Low (1972) nominated the type section in petroleum well Eneabba 1 (MGA Zone 50, 338446 m E, 6727627 m N) from 1790 to 2302 m, and it was subsequently revised by Mory and Iasky (1996).

The Cattamarra Coal Measures were previously defined as the Cattamarra Coal Member (Willmott 1964) within the upper part of the Cockleshell Gully Formation (Table 9). The use of the name 'Cockleshell Gully Formation' was discontinued and the member reclassified as a formation (Mory 1994a). In the Geraldton area and over the Northampton Inlier, the Moonyoonooka Sandstone of the Chapman Group described by Arkell and Playford (1954) is largely equivalent to the Cattamarra Coal Measures (Playford et al. 1976). The use of the names 'Chapman Group' and 'Moonyoonooka Sandstone' is discontinued, and the Moonyoonooka Sandstone is now considered part of the Cattamarra Coal Measures. The Jurassic sediments below the Nabawa Sandplain (Koomberi 1995) are now correlated with the Cattamarra Coal Measures.

The Cattamarra Coal Measures consist of very fine to very coarse grained sandstone with thick beds of dark grey, carbonaceous siltstone, claystone, and coal seams of up to 11 m thickness (Playford et al. 1976; Mory & Iasky 1996). The sandstone is grey, very fine to very coarse grained, moderately to poorly sorted, subangular to subrounded, in parts pyritic, kaolinitic and feldspathic, and often clayey. However, in outcrop, coarse-grained sand units are interbedded with fine to very fine sandstone and siltstone, with cross-bedding (Mory 1995b). The siltstone, claystone and shale beds are medium to dark grey and brown-grey, often carbonaceous and laminated. In outcrop, the Cattamarra Coal Measures is generally weathered to a yellowish to red-brownish colour.

The Cattamarra Coal Measures lie conformably between the overlying Cadda or Yarragadee formations and underlying Eneabba Formation (Playford et al. 1976; Mory & Iasky 1996). Near the northern margins of the basin, the formation can unconformably overlie the Kockatea Shale, Woodada Formation, or Proterozoic granite and gneisses of the Northampton Inlier (Playford et al. 1970; Mory 1995b). The presence of thick, carbonaceous siltstone, claystone and shale units distinguish it from the underlying Eneabba Formation (Mory 1995; Mory & Iasky 1996) and these are evident on downhole gamma-ray logs as thick sections of high gamma count, interspersed with typically thinner intervals of low count over sandstone portions (Figure 25 and Figure 26) (Mory 1995). It can be difficult to identify the Cattamarra Coal Measures from the overlying Cadda Formation, unless the characteristic limestone of the Cadda Formation is present.

Deposition of the Cattamarra Coal Measures was in a non-marine, lacustrine deltaic to fluvial setting. The fine-grained siltstone and claystone, and coal seams, are local bay-filled deposits while the thicker sandstone beds, particularly those overlying the coal seams, are probably delta plain deposits (Mory & Iasky 1996). The depositional setting progressed from a near-source braided river to an estuarine/lacustrine meandering river from the south-east to north-west (Tarabbia 1991). Microplankton within the upper portion suggests some marine influences in the northern part of the basin (Young et al. 1974).

Palynomorph assemblages belong to the upper *Corollina torosa* and lower *Callialasporites turbatus* zones (Mory & Iasky 1996). They may also extend into the *Dictyophyllidites harrisii* miospore assemblage subzone or the lower *Dictyotosporites complex* miospore zone identified in Gillingarra Line GL8 (Moncrieff 1989). These assemblages suggest a Pliensbachian to Aalenian age (Early to Middle Jurassic) (Mory & Iasky 1996), possibly extending into the Bajocian. Fossil wood, leaves and rare bivalves, branchiopods and insects are present. Bioturbation of beds is also common (Mory 1994a).

The Cattamarra Coal Measures are widespread in the subsurface through most of the northern Perth Basin, extending offshore into the Vlaming and Abrolhos sub-basins (Crostella 2001). The formation outcrops on the Cadda Terrace and Greenough Shelf, and onlaps the Northampton Inlier where it was formerly known as the Chapman Group. The main exposures are near Geraldton (Allen 1980), on the Nabawa Sandplain (Koomberi 1995), at Mount Hill (Mory & Iasky 1996; Lowry 1974) and in the Hill River area (Playford et al. 1976). Outcrops are also at the southern onshore end of the Gascoyne Platform of the Carnarvon Basin. The formation subcrops the superficial formations between Cliff Head and Eneabba, and from Mt Hill to the Oakajee River, north of Geraldton (Figure 18). The formation is absent over the Irwin Terrace (including the Mullingarra Inlier) and Coolcalalaya Terrace in the east, and upon the Beagle Ridge south of about Coolimba in the west, where the formation was either not deposited or has been fully eroded.

Based on seismic and gravity data, the depth to the top of the Cattamarra Coal Measures reaches a maximum of 5600 m within the eastern Dandaragan Trough north-west of Moora and shallows to the west and in the more northern parts of the basin (Mory & Iasky 1996). The thickest sections of the Cattamarra Coal Measures are in the south, reaching almost 1200 m in petroleum well Cataby 1, although Mory and Iasky (1996) suggest it may be up to 1500 m thick at this location. The formation becomes thinner to the north and west, to be less than 200 m thick near Geraldton and about 35 m thick east of Geraldton (Mory 1995b; Mory & Iasky 1996).

4.15 Cadda Formation

The Cadda Formation, named by Playford and Willmott (1958) is a Middle Jurassic marine sequence of siltstone, sandstone, shale, claystone and fossiliferous limestone. The Champion Bay Group, described by Arkell and Playford (1954), present about the northern margin of the Perth Basin, and is considered as part of the Cadda Formation in this bulletin (Table 9). It is located 0.4 km west of Cadda Spring (MGA Zone 50, 333630 m E, 6635140 m N).

The Cadda Formation consists of sandstone, siltstone and shale, grading in places into sandy shelly limestone. The sandstone is white, pale grey and green-grey, fine to coarse grained, and contains some kaolin matrix. Interbeds of very fine to medium grained and moderately well-cemented sandstone are common. Sandstone in the middle to lower portion of the formation is fine to medium grained, friable to hard and contains glauconite with minor siliceous and calcite cementation. The siltstone is medium to dark grey, with some thin beds of very fine to fine-grained, white to green–grey micaceous sandstone. Minor coal and claystone is present within the upper part, while claystone, shale and siltstone are more abundant within the middle and lower parts of the formation. The claystone and shale is brown-grey and the lower part probably correlates to the Bringo Shale of the Champion Bay Group. Limestone beds are sometimes present in the upper part of the claystone and shale portion of the formation, and occasionally grade into calcareous sandstone (Playford et al. 1976; Mory & Iasky 1996). The limestone beds are yellow-brown and grey, firm to hard, and richly fossiliferous containing predominantly small bivalves (especially oysters) and some ammonites (Arkell & Playford 1954; Playford et al. 1976). The limestone becomes more conspicuous to the north, closer to the Northampton Inlier. In outcrop, the limestone is ferruginised and leached of carbonate with moulds of small molluscs. Fossiliferous beds are equivalent to the Newmarracarra Limestone within the Champion Bay Group (Arkell & Playford 1954).

The Cadda Formation lies conformably between the Cattamarra Coal Measures and the Yarragadee Formation (Playford et al. 1976). However, in the northern parts of the basin where the Cattamarra Coal Measures and Eneabba Formation are absent, the Cadda Formation disconformably overlies Kockatea Shale or Proterozoic basement. Downhole geophysical logs typically show a high gamma-ray count, distinguishing it from the overlying Yarragadee Formation (Figure 27). The gamma-ray count is often higher compared to shale of the underlying Cattamarra Coal Measures, due to the presence of glauconite (Mory & Iasky 1996), but resolving the contact with the Cattamarra Coal Measures is often difficult without palynological data.

The Cadda Formation was deposited in a marine to marginal marine setting (Playford et al. 1976). The sequence initially represents a marine transgression, progressing into an open shallow sea setting, and then prograding back to marginal marine conditions at the top of the sequence. Playford et al. (1976) described a similar succession of marine environments for the Champion Bay Group in the southern Carnarvon Basin where the basal Colalura Sandstone represents shallow-water deposits at the start of the marine transgression, followed by the Bringo Shale and Newmarracarra Limestone that were laid in a shallow sea environment with restricted circulation, and finally the top Kojarena Sandstone that was deposited in a shallow water to marginal marine environment.

Spores and pollen from the Cadda Formation belong to the *Dictyotosporites complex* and upper *Callialasporites turbatus* zones, and dinoflagellates are of the *Dissiliodinium caddaensis* Zone (Backhouse 1992a). Macrofossils and microfossils suggest Middle Jurassic, of Aalenian to Bajocian age (Playford et al. 1976; Backhouse 1992a).

The Cadda Formation is extensively distributed throughout the northern Perth Basin. The Cadda Formation outcrops upon the Cadda Terrace in the Gairdner Range near the Hill River and towards Eneabba. It also outcrops where it onlaps the Northampton Inlier and along the Greenough River as far east as the Urella Fault. There are minor outcrops at Enanty Hill near Mingenew and Mount Hill on the Greenough Shelf.

The formation has been encountered at depth on the Barberton Terrace in the Gillingarra Line GL8 (Moncrieff 1989) and extends into the Beermullah Trough (Crostella & Backhouse 2000). The Cadda Formation is absent on the Beagle Ridge south of Cliff Head, and over the Irwin and Coolcalalaya terraces.

The depositional centre of the Cadda Formation is in the central part of the onshore northern Perth Basin to the south of Eneabba (Mory & Iasky 1996). There is considerable uncertainty about the thickness of the Cadda Formation because the contact with the underlying Cattamarra Coal Measures is difficult to identify. Many reported intersections are likely to be overestimated. The maximum reported thickness is 290 m in petroleum well Mullering 1 and 288 m in petroleum well Ocean Hill 1 (Mory & Iasky 1996). The formation thins to less than 50 m north of Dongara (Mory & Iasky 1996).

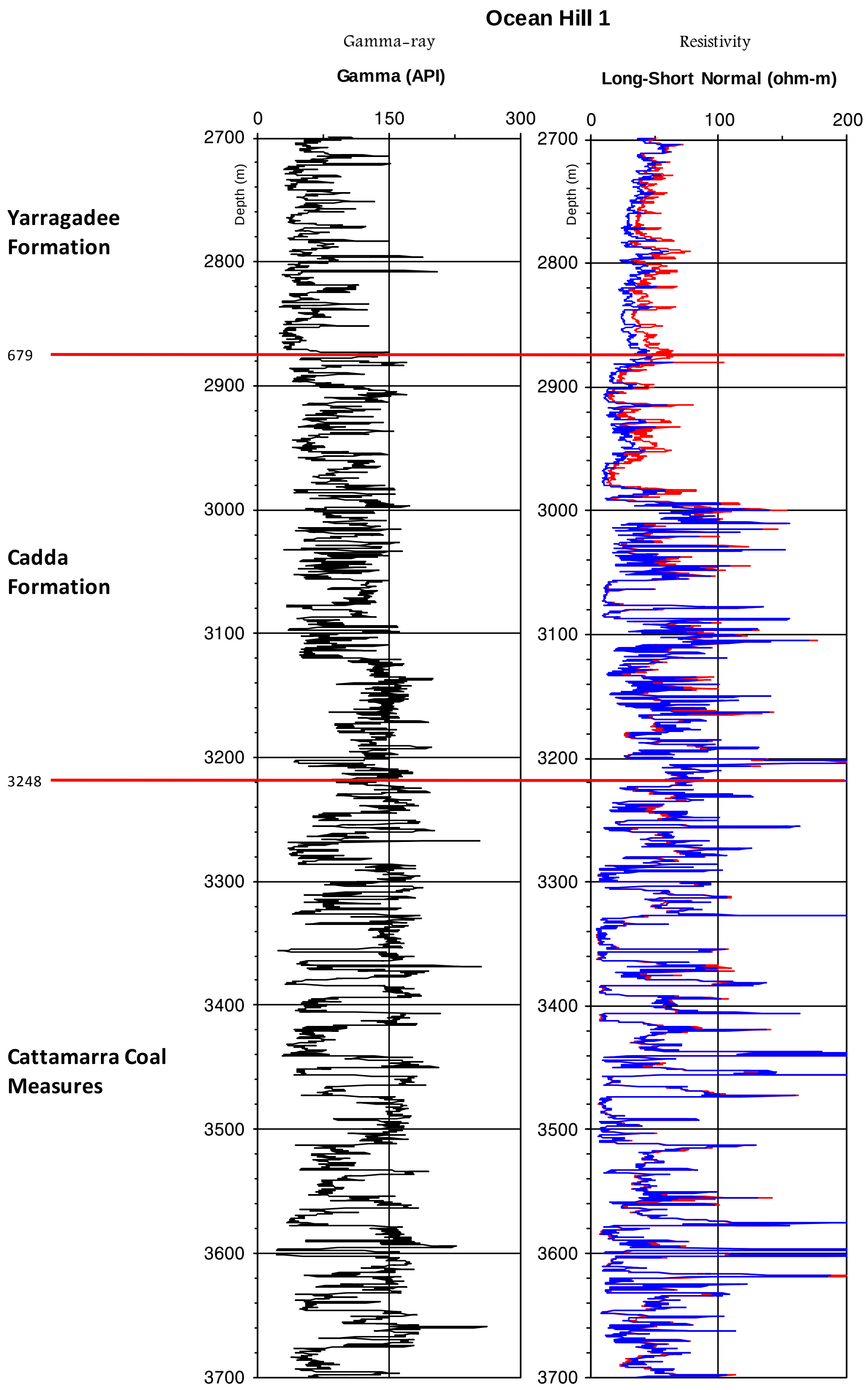


Figure 27 Downhole geophysical log of petroleum well Ocean Hill 1 (2700–3700 m bgl) showing the Cadda Formation

4.16 Yarragadee Formation

The Yarragadee Formation is a Middle to Late Jurassic, predominantly sand unit, which consists of interbedded sandstone, siltstone, shale and claystone beds with minor conglomerate. Sediments were deposited in a non-marine fluvial environment, with shale sections possibly representing a lacustrine or overbank setting (Mory & Iasky 1996). Facies analysis of petroleum well Gingin 1 near Gingin indicates that the Yarragadee sediments were deposited in a perennial braided river system with a high sediment load similar to the modern Brahmaputra River of Pakistan (McArthur 2009).

The name ‘Yarragadee Beds’ was introduced by Fairbridge (1953) for exposures of sandstone and siltstone on Yarragadee property, 12 km north of Mingenew. It was amended to Yarragadee Formation by Playford, Willmott and McKellar (*in* McWhae et al. 1958), and redefined by Backhouse (1984) to exclude the Parmelia Formation. A subsurface reference section was given in Gingin No. 1 well as 356–3315 m (Playford et al. 1976; amended Backhouse 1984). Previously, the portion below the Otorowiri Formation of the Yarragadee Formation was referred to as the Lower Yarragadee Formation (Commander 1978a, 1978b).

Sandstone beds in the Yarragadee Formation are typically thick and cross-bedded with thin lenticular clays and shale. Individual sand beds are typically discontinuous, and range in thickness to over 40 m (Nidagal 1995), but average about 10 m thick in the Allanooka area (Allen 1980). The sandstone beds consist of pale brown, pale grey to grey, very fine to very coarse grained and granular sand, variably feldspathic quartz sand, which is poorly to moderately sorted, angular to subrounded, and typically weakly cemented. It is often kaolinitic, particularly near the surface in outcrop areas (Irwin 2007). Lower portions of the formation contain minor mica, pyrite, garnet and heavy minerals, with garnet comprising up to 5 per cent in some beds (Moncrieff 1989). Thin layers of pyrite-cemented sandstone and thin laminae of coal are common.

The siltstone and shale beds are of similar thickness to the sandstone beds, usually laminated, and commonly sandy, pyritic and micaceous (Allen 1981). The siltstones are light to dark brown, grey and rarely green in colour. The shale beds are dark grey to black and carbonaceous, with thin coal beds of less than one metre thickness (Harley 1974).

In outcrop, the Yarragadee Formation is typically oxidised to considerable depths. Oxidation was observed as deep as 400 m below the surface along the Watheroo Line, between 100 and 200 m along the Eneabba and Dongara lines (Commander 1981; Irwin 2007), and to some distance below the watertable in the Allanooka area (Allen 1980). In the oxidised zone, the formation is white, cream, red or yellow-brown in colour. Feldspar within the weathered zone is altered to kaolin clay, pyrite is oxidised to ferruginous layers or nodules, and a laterite profile is often developed at the surface (Allen 1980).

The Yarragadee Formation is between 2000 m and 3700 m thick between Gingin and Mingenew except along the eastern margin of the basin, with the greatest thickness north-west of Moora where a maximum of 3693 m was intersected in petroleum well Warro 2. The Yarragadee Formation thins considerably to the west onto the Beagle Ridge, and north towards the Allanooka High. The Yarragadee Formation is absent north of the Greenough River.

Palynological assemblages within the Yarragadee Formation range from the miospore zonations *Dictyotosporites complex* Zone up to the *Aequitriradites acusus* miospore zone as defined by Backhouse (1988). These indicate a non-marine environment and a late Bajocian to Tithonian age. Sandy lithologies retain sparse palynological assemblages or are barren, but may contain wood fragments.

Several units are identifiable within the Yarragadee Formation based on lithology and palynology, and can be mapped throughout the northern Perth Basin. Craig (1990) recognised alternating fluvial and lacustrine sequences in petroleum wells Warro 1 and 2 that allowed its subdivision into units. Pennington Scott (2010) defined and informally referred to them as units A, B, C and D, in order of oldest to youngest. This classification has been adopted in this publication.

Units A and C contain predominantly sandstone sequences and are predominantly fluvial deposits. Unit A contains about 30 per cent siltstone and shale beds, but these are only minor in Unit C. Unit B contains 60–70 per cent siltstone and shale and are interpreted as lacustrine deposits. Unit D comprises up to 80 per cent fine-grained sediments that probably represent lacustrine deposits.

Representative downhole geophysical logs of the Yarragadee Formation from petroleum wells Warro 1 and Ocean Hill 1 are presented in Figure 28 and Figure 29 showing each of the units. High gamma-ray count associated with units B and D reflects the dominant clay lithology, and lower gamma-ray count against the A and C units suggests a sandier lithology. In general, the gamma-ray count in the Yarragadee Formation is lower than in the underlying Cadda Formation and Cattamarra Coal Measures where the gamma-ray count is more likely in the order of 100–150 API. However, the gamma-ray signature in the Gage Sandstone is often difficult to distinguish from the signature in the Yarragadee Formation because the Gage Sandstone represents an erosional surface of the Yarragadee Formation. Resistivity logs in the Yarragadee Formation are affected by the groundwater quality and is generally high, 50–100 Ωm, at the top of the formation where groundwater is generally fresh. However, the resistivity diminishes with depth while the salinity increases with depth and is it generally lowest in clayey strata.

The Yarragadee Formation is distributed throughout most of the northern Perth Basin (Figure 30, Figure 31, Figure 32 and Figure 33). The structural base elevation for the formation is equivalent to the base of Yarragadee Formation Unit A except in the northernmost parts of the Bookara Shelf where Unit A is likely absent and the base of Unit B forms the base of the Yarragadee Formation (Schafer 2016). The formation extends to about -4700 m AHD at its deepest within the eastern portion of the Dandaragan Trough, based on petroleum wells Warro 1 and 2 that fully penetrated the formation, as well as seismic interpretations and gravity data from Mory and Iasky (1996). The base of the formation rises to the west and north, reaching over 100 m AHD at its northern margin on the Wicherina Terrace, Bookara Shelf and Greenough Shelf. It is absent within the Beagle and Irwin terraces.

The Yarragadee Formation lies conformably upon the underlying Cadda Formation or Cattamarra Coal Measures, and is conformably overlain by the Otorowiri Formation of the Parmelia Group within the eastern Dandaragan Trough. It is unconformably overlain by the Warnbro Group in the south-west, by the superficial formations on the coastal plain north of

Eneabba, and in a small area in the south near Cataby. East of the Gingin Scarp, the Yarragadee Formation is exposed at the surface over the Arrowsmith region and Victoria Plateau, typically with a thin surficial cover and weathered profile. Upon the Cadda Terrace, the Yarragadee Formation abuts the Cattamarra Coal Measures along faulted contacts in the western portion of the terrace. Along the eastern boundary, the Yarragadee Formation abuts Archean crystalline rocks of the Yilgarn Craton at the Darling Fault, or Permian formations at the Urella Fault.

Unit A

Unit A of the Yarragadee Formation forms the basal portion of the formation. The reference section is between 3354 and 4331 m depth in petroleum well Warro 1 (MGA Zone 50, 378470 m E, 6662018 m N). Unit A comprises mainly medium- to coarse-grained, poorly to moderately sorted sandstone (about 70%), with beds of coarse to very coarse sandstones and very fine to fine sandstones. Unit A has moderate siliceous cementation and a kaolin matrix is common, although the clay is often not apparent in mud rotary drill samples. Some carbonate cementation is recorded toward the base (Young et al. 1978). Fine-grained sandstone beds are light grey, silty, kaolinitic, micaceous, friable, and often interlaminated with siltstone. The feldspar content of the sandstone is typically 20–25 per cent, but can reach 40 per cent of fresh and kaolinised feldspar over intervals (Pudovskis 1962). Unit A contains beds of siltstone and shale/claystone, up to about 20 m thick, which are light to dark grey-brown and grey-black, firm, silty, micaceous and carbonaceous. Unit A also contains occasional thin beds and laminations of very fine, silty sandstone.

Unit A is a fluvial deposit with sandstones forming stacked upward-fining sequences associated with channel deposits; and the siltstone and clay/shale intervals reflect overbank deposits. Palynological assemblages within Unit A belong to the *Dictyotosporites complex* Zone of Bajocian age.

The average thickness of Unit A intersected by fully penetrating drill holes is 387 m, with a maximum of 1095 m in petroleum well Gingin 1. Palynology data indicates that Yarragadee Unit A is either absent or very thin north of the Bookara Fault (Schafer 2016). The base elevation for Unit A, which forms the base of the Yarragadee Formation, is shown in Figure 30.

Downhole gamma-ray logs for Unit A have a diffused low gamma-ray count centred on 50 API, with interspersed peaks associated with shale/claystone horizons up to 150 API (Figure 28 and Figure 29). The high resistivity in Unit A in petroleum well Warro 1 between 3800 and 4300 m bgl is due to entrapped natural gas.

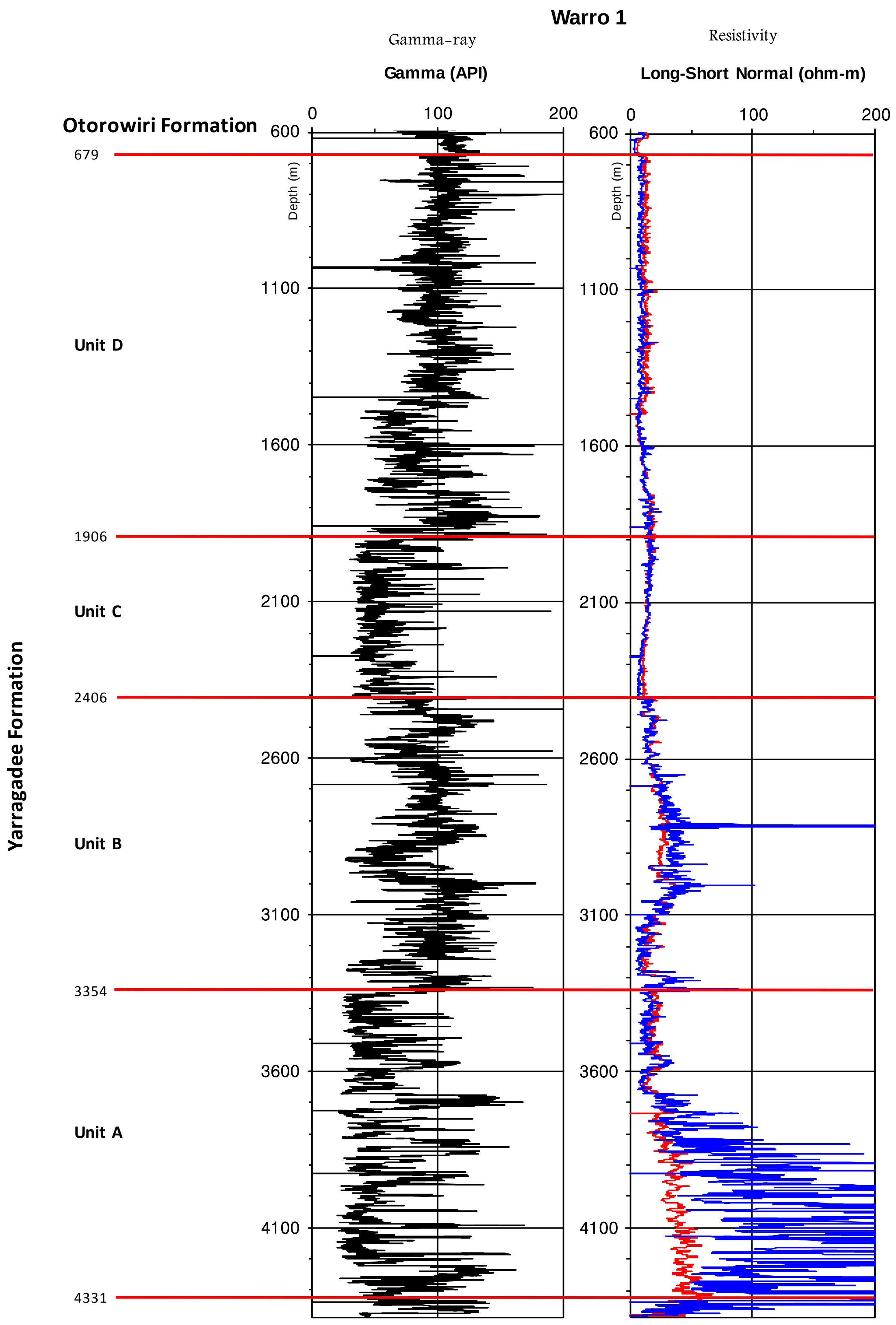


Figure 28 Downhole geophysical log of petroleum well Warro 1 (600–4385 m bgl) showing the Yarragadee Formation

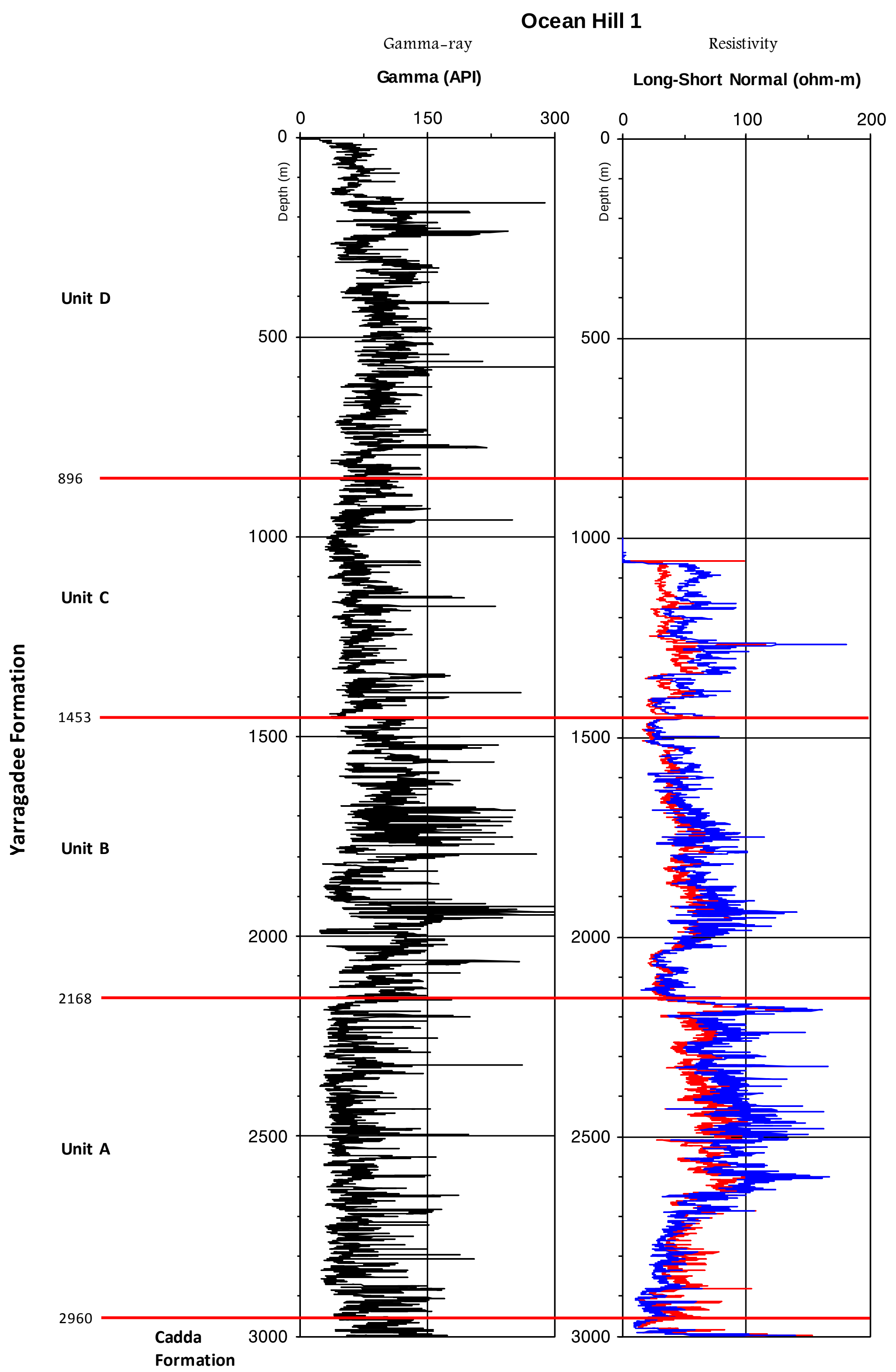


Figure 29 *Downhole geophysical log of petroleum well Ocean Hill 1 (0–3000 m bgl) showing the Yarragadee Formation*

Unit B

Unit B of the Yarragadee Formation, which overlies Unit A, is an argillaceous sequence containing about 60–70 per cent siltstone and shale/claystone layers. The reference section is within petroleum well Warro 1 between 2406 and 3354 m (MGA Zone 50, 378470 m E, 6662018 m N).

The siltstone in Unit B is grey with thin laminations of very fine, well-cemented, argillaceous sandstone (Johnson 1965) grading to claystone and shale that is dark brown-grey, micaceous, carbonaceous and pyritic that are up to about 20 m thick. The sandstone in Unit B is similar to that in units A and C; poorly to moderately sorted, angular to subangular, feldspathic with moderate development of siliceous cement. Kaolin clay is common, and is more abundant in the lower part of the unit. The sandstone also has coal laminae. A thicker sandstone interval is present within the central portion of the unit and is typically 100–200 m thick. This sandstone interval has been encountered in many petroleum wells in the central to southern Dandaragan Trough.

Unit B was deposited in lacustrine environments, with periods of deltaic and fluvial influence. Palynological assemblages within Unit B are from the *Contignisporites cooksoniae* miospore zone, indicating a Bathonian to early Callovian age.

Downhole gamma-ray logs show higher count over intervals dominated by shale and claystone with intermediate levels possibly representing siltstone and clayey sandstone (Figure 28 and Figure 29). There are also sections of low gamma-ray count associated with sand-dominated intervals that can contain substantial silt and kaolin clay. Overall, the gamma-ray signature in Unit B is tighter than in Unit A (below) and Unit C (above), and is centred on 100 API.

An average thickness of 350 m has been intersected by fully penetrating drill holes. The maximum thickness of 967 m was intersected in petroleum well Warro 2. Figure 31 shows the basal elevation for Unit B, which at its deepest reaches about –3700 m AHD at the eastern margin of the Dandaragan Trough, rising to the west. Recent investigations show Unit B is present north of the Bookara Fault, directly overlying the Cadda Formation, as Unit A is absent or very thin (Schafer 2016).

Unit C

Unit C is a distinctive, thick sandstone sequence that overlies the shale and claystone of Unit B. Unit C comprises about 80 per cent sand. The reference section is within petroleum well Warro 1 between 1906 and 2406 m depth below ground (MGA Zone 50, 378470 m E, 6662018 m N).

The sandstone is a light brown to light grey, medium to very coarse grained quartz sand with fine-grained intervals, with some gravel and pebbles and minor feldspar. It is poorly to well sorted (but mainly moderately sorted), subangular to subrounded, and mostly unconsolidated. There is minor kaolin clay in the matrix, minor siliceous cementation, and rare thin beds of grey to brown-grey, micaceous, slightly carbonaceous siltstone and black coal.

Unit C was deposited in a fluvial and alluvial setting during a tectonically active period accompanied by a large influx of sand (Craig 1990). The palynology belongs to the *Murospora florida Z*one, and ranges from Callovian to Kimmeridgian in age.

Downhole gamma-ray logs have a characteristic low count over the sequence, centred on 50 API, containing minor peaks corresponding to clay and siltstone intervals (Figure 28 and Figure 29). There is typically an abrupt contact with higher gamma-ray count of units B and D.

Unit C has an average thickness of 350 m and a maximum of 719 m (petroleum well Gingin 1). The deepest portion is about –2700 m AHD in the eastern Dandaragan Trough, shallowing to the west (Figure 32). Unit C is absent on the Cadda Terrace where this part of the Yarragadee Formation has been eroded (Schafer 2016).

Unit D

Unit D is a sequence of interbedded sandstone, claystone and siltstone overlying Unit C. The reference section is in petroleum well Warro 1 between 679 and 1906 m depth (MGA Zone 50, 378470 m E, 6662018 m N).

The sandstone within the upper portion of Unit D is white to light grey and pale greenish grey, silty to fine grained, friable to hard, silty in part, with a kaolin clay matrix. It is variably calcareous, rarely grading into light brown sandy limestone with occasional beds of loose, coarse to very coarse quartz sand.

Deeper in the unit, the sandstone is fine to very coarse grained, moderately to poorly sorted, subangular to subrounded, with some siliceous cement. Intervals of silty, fine-grained sand similar to the upper sandstone are also present. There is minor brown to black coal, and occasionally pyrite. Much of the deeper sandstone contains a portion of silt and kaolin clay that is not always apparent in mud rotary drill samples.

Interbedded siltstones are light to dark brown-grey, grading to dark brown-grey claystone that is soft to firm. Siltstone and claystone are dominant within the upper part of Unit D as far north as the Eneabba Line. The lower 150 m of Unit D south of petroleum well Yallalie 1 is mainly siltstone.

Unit D is a lacustrine deposit with fluvial interruptions. Palynological assemblages belong to the miospore zone *Retitriletes watherooensis* and the Tithonian age *Aequitriradites acusus* Zone. Downhole gamma-ray logs have a tight signature centred on 100 API and contrast with more diffused and lower gamma-ray counts in units A and C.

The full sequence of Unit D has been intersected beneath the Dandaragan Plateau with an average thickness of 930 m and a maximum of 1743 m in petroleum well Yallalie 1. Unit D has a maximum depth of about –2200 m AHD at the eastern margin of the Dandaragan Trough (Figure 33). The unit shallows to the west and extends into the Coomallo Trough and Allanooka High. Unit D is absent over the western onshore portion of the basin, where it has probably been fully eroded by the breakup unconformity.

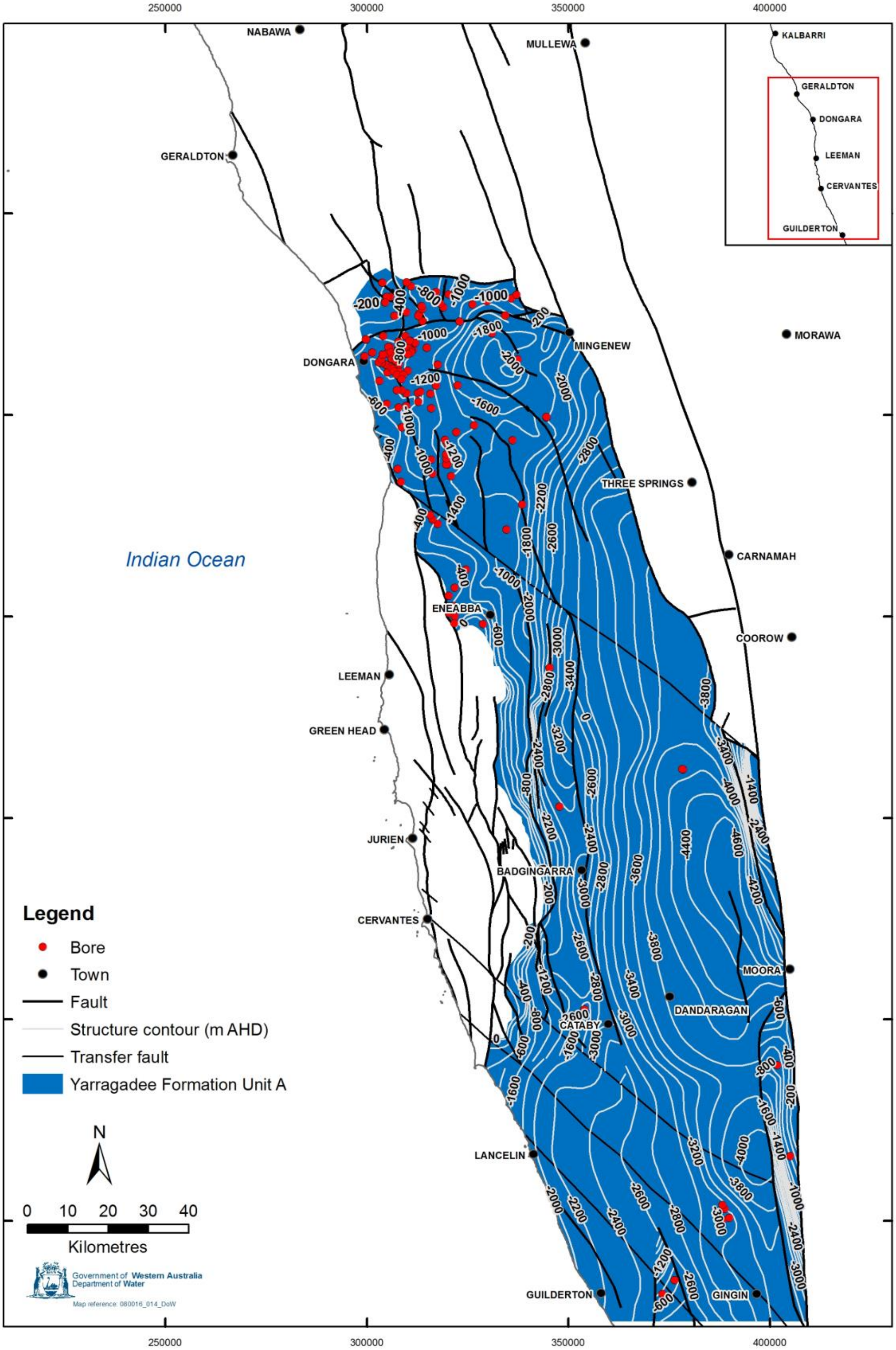


Figure 30 Yarragadee Formation Unit A: contours on base of unit

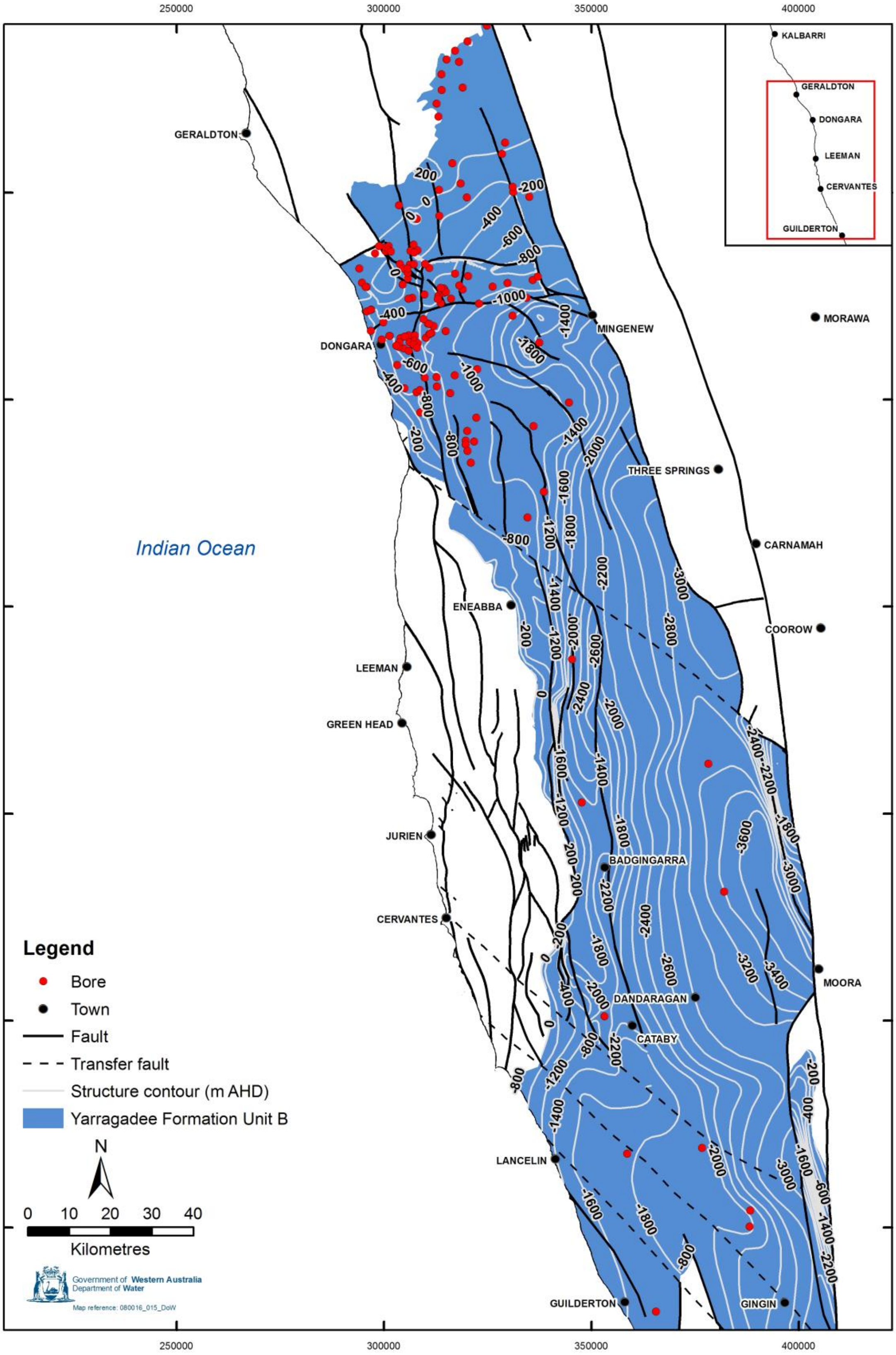


Figure 31 Yarragadee Formation Unit B: contours on base of unit

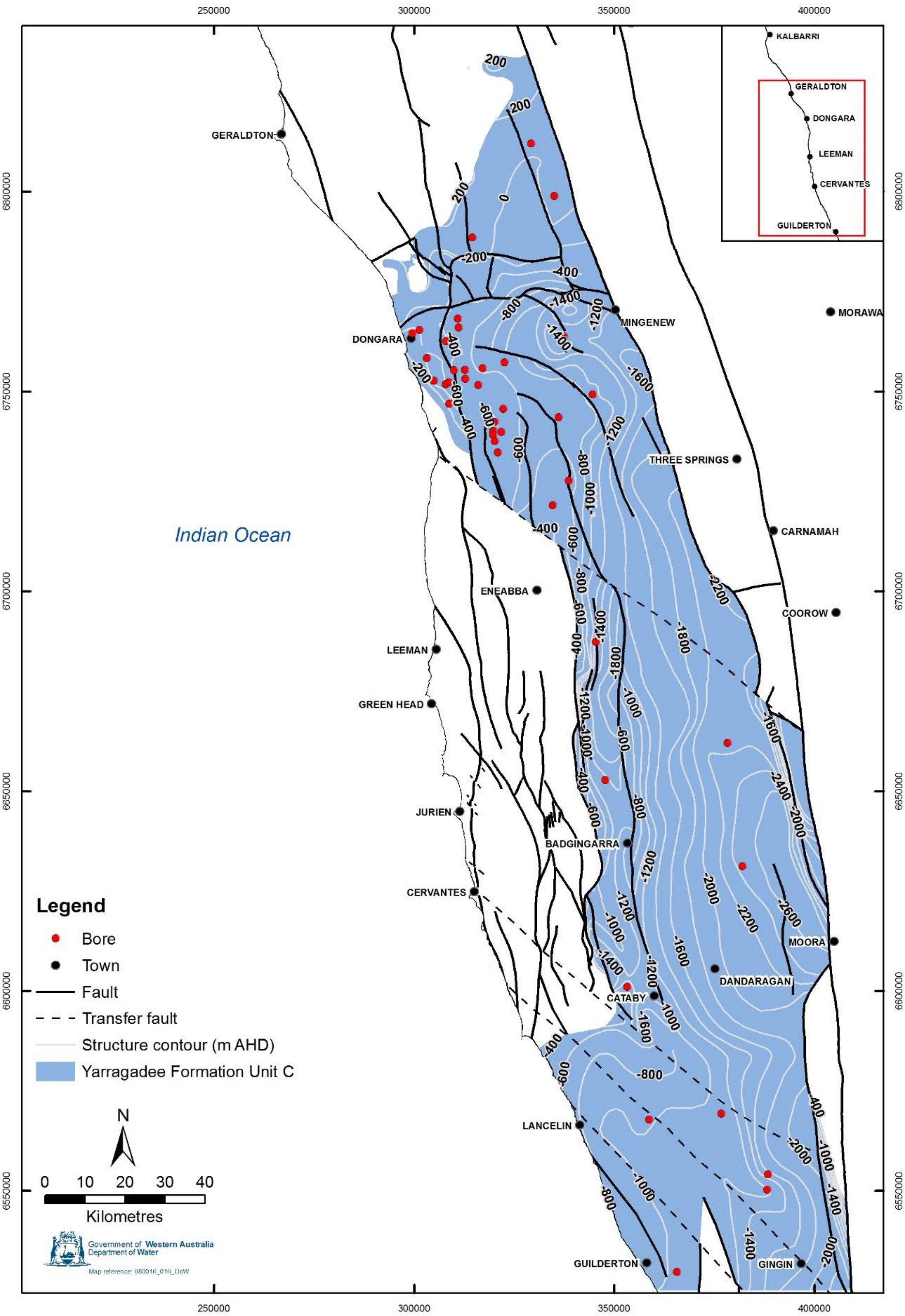


Figure 32 Yarragadee Formation Unit C: contours on base of unit

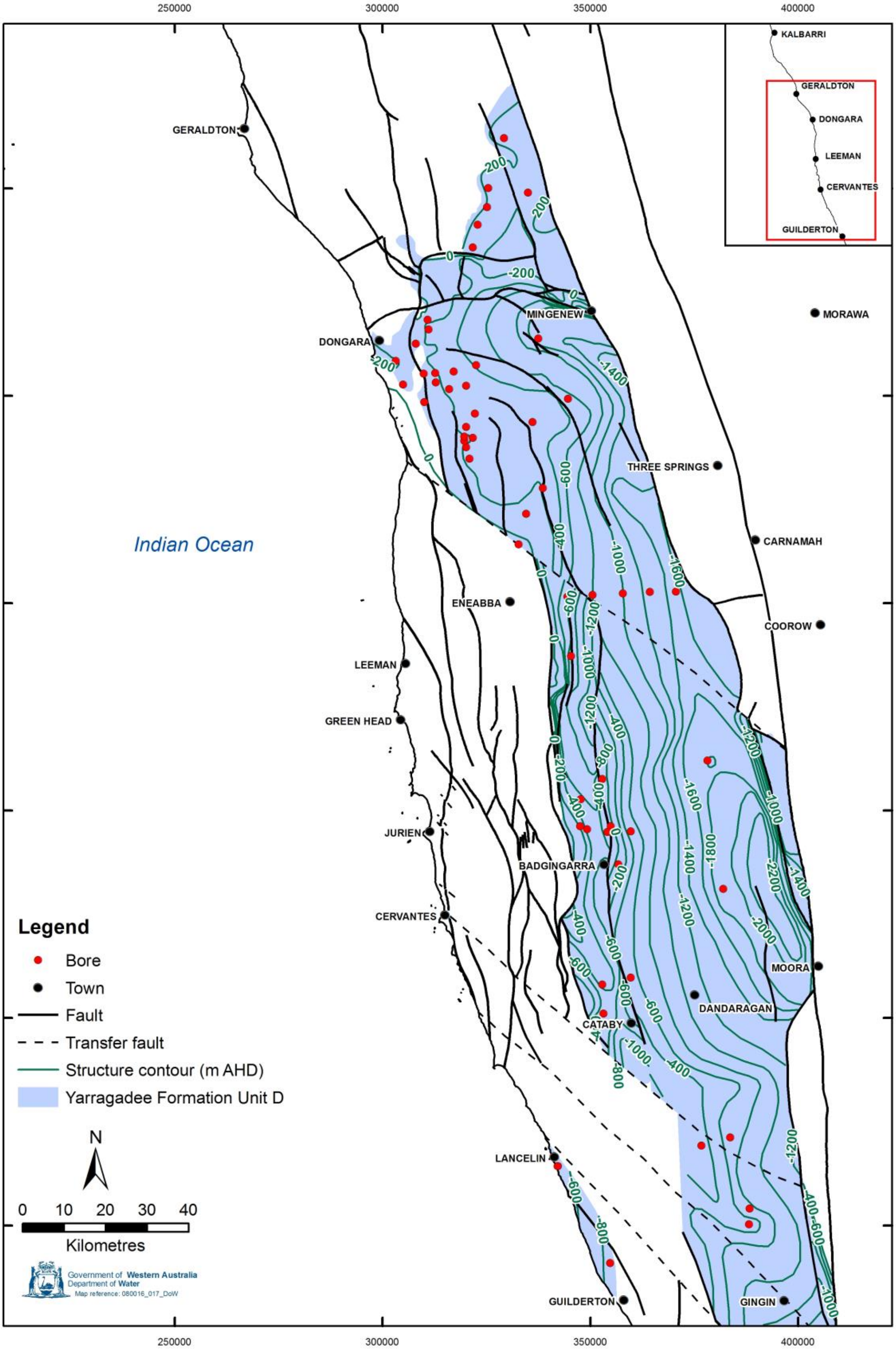


Figure 33 Yarragadee Formation Unit D: contours on base of unit

4.17 Parmelia Group

The Parmelia Group consists of sandstone, siltstone and shale that were deposited across the east of the northern Perth Basin in a fluvial to lacustrine environment during the Early Cretaceous. The name Parmelia Group was proposed by Crostella and Backhouse (2000), while previous member units of the Parmelia Formation, as defined by Backhouse (1988), were recognised as new formations. The group was previously described as part of the Yarragadee Formation (Playford et al. 1976). The formations within the Parmelia Group identified in offshore oil exploration wells are, in ascending order: the Otorowiri Formation, the Jervoise Sandstone, the Carnac Formation and the Charlotte Sandstone.

The Otorowiri Formation is the most widespread formation and forms the base of the Parmelia Group, and its outcrop can be traced from Mingenew to Dandaragan. In the south and centre of the area, the Otorowiri Formation is overlain by the shaley Carnac Formation. In the north and to the east, the Otorowiri Formation is overlain by an interbedded sand and subordinate shale, which is not found offshore. The Jervoise and Charlotte sandstones have not been recognised onshore. It is often difficult to distinguish the various formations above the Otorowiri Formation onshore, particularly in the Dandaragan and Beermullah troughs, and they are referred to as ‘undifferentiated Parmelia Group’ in this bulletin.

Sediments of the Parmelia Group were deposited within fluvio-deltaic and extensive lacustrine environments (Backhouse 1988). Based on palynological evidence, the siltstone and shale units that dominate the Otorowiri and Carnac formations are considered to be open, freshwater deposits (Backhouse 1988). In outcrop, the sediment beds are lenticular, variable in composition, and have limited lateral extent, with cross-bedding and slump structures evident.

Downhole gamma-ray logs through the Parmelia Group show distinctive fairly high count through the shaley Otorowiri and Carnac formations that distinguishes it from the more variable units above and below (Figure 34). The shale is notoriously prone to swelling, resulting in drilling problems.

The palynology of the Parmelia Group belongs to the *Biretisporites eneabbaensis* miospore zone and *Fusiformaccysta tuminda* microplankton zone (Backhouse 1988), which are Tithonian to Berriasian age of the upper Late Jurassic to lower Early Cretaceous. Dinoflagellate cysts are non-marine and associated with large lakes that were extensive across the Perth Basin at this time. Reworked Permian and Early Jurassic palynomorphs are also common.

Parmelia Group sedimentation was widespread within the Perth Basin, but much of the onshore portion was eroded during basin uplift in the final stage of continental breakup in the early Neocomian. The group is preserved within the eastern portion of the Dandaragan and Beermullah troughs and has a maximum known onshore thickness of 829 m in Gillingarra Line GL7 (Moncrieff 1989). The Parmelia Group is present over a large area offshore in the Vlaming Sub-basin where it can be over 2000 m thick and has been encountered in an onshore extension of the sub-basin at Guilderton within Artesian Monitoring AM1.

The Parmelia Group extends to a depth of –1400 m AHD at the eastern margin of the Dandaragan Trough, and rises to the western margin and within the northern area of its extent, reaching a maximum elevation of over 200 m AHD (Figure 35). The Parmelia Group subcrops beneath thin surficial deposits over the northern and western portions of the Dandaragan Plateau and outcrops along the Dandaragan Scarp (see Figure 18).

The Parmelia Group conformably overlies the Yarragadee Formation. It is disconformably overlain by the Warnbro Group and locally by the Coolyena Group in the south-west of the northern Perth Basin where the Warnbro Group is absent.

Otorowiri Formation

The Otorowiri Formation is characterised by shale and siltstone at the base of the Parmelia Group. It was first recognised in water bores in the Arrowsmith River area (Barnett 1970b). Ingram (1967) described it as the Otorowiri Siltstone Member of the Yarragadee Formation. The siltstone and shale unit was subsequently identified onshore within the Eneabba Line (Commander 1978a, 1978b) and extensively in offshore petroleum wells in the Vlaming Sub-basin. The type section is from 253 to 277 m depth in Arrowsmith River 25 (MGA Zone 50, 358301 m E, 6730642 m N) in the northern Dandaragan Trough. The Otorowiri Formation outcrops along the Dandaragan Scarp, which extends from Mingenew to Cataby.

The Otorowiri Formation comprises shale and siltstone with minor thin beds of fine-grained sandstone. The shale and siltstone is finely laminated, predominantly dark grey to greenish-grey, and micaceous, while the sand is glauconitic and pyritic (Playford, et al. 1976). In the Eneabba Line, there are two distinct siltstone beds separated by a thin sand horizon (Commander 1981).

Gamma-ray logs show a distinctive, fairly high count through the Otorowiri Formation that distinguishes it from the more variable units above and below (Figure 34). There is a corresponding low resistivity value within the formation. There is frequently a difference in resistivity between the upper and lower portions, with a slightly higher resistivity associated with increased siltstone and fine-grained sandstone.

The Otorowiri Formation was deposited during the Late Jurassic Tithonian age (Backhouse 1988). It was deposited in a lacustrine environment with some periods of marine lagoonal conditions as indicated by the presence of non-marine dinoflagellate cysts (Backhouse 1982) and marine dinoflagellates (Moncrieff 1989; Discovery Petroleum 1995b). Characteristically, there are some older microflora reworked from pre-existing formations.

The formation thickens southward from about 30 m near the Arrowsmith River (Barnett 1969) to 102 m in Eneabba Line EL2A. To the south of the Eneabba Line, the formation is less distinct and difficult to distinguish from overlying shale of the Carnac Formation. Contours on the base of the Otorowiri Formation are presented in Figure 35, which also represents the base of the Parmelia Group.

The Otorowiri Formation conformably overlies the Yarragadee Formation. It is overlain conformably by the Carnac Formation or 'undifferentiated Parmelia Group', and unconformably by the Warnbro Group between Moore River and Gingin Brook.

Carnac Formation

The Carnac Formation is a thick shale and siltstone sequence. It was originally defined as the Carnac Member of the Parmelia Formation by Backhouse (1984) and later elevated to formation status by Crostella and Backhouse (2000). Three members of the formation were described: the Stragglers, Mangles and Hawley members, in ascending order. Earlier descriptions of the formation referred to it as the Quinns Shale Member of the Yarragadee Formation (Bozanic 1969; Playford et al. 1976), but this terminology was abandoned by Backhouse (1984), who separated the Parmelia Formation from the Yarragadee Formation. The type section is between 2408 and 3064 m depth in offshore petroleum well Peel 1 (Backhouse 1984). Separate type sections are provided for the individual members in Crostella and Backhouse (2000).

The Carnac Formation comprises light to dark brownish grey, moderately consolidated siltstone, shale and claystone, with minor sandy layers. The sediments are slightly micaceous, with traces of pyrite and glauconite, and are laminated.

Within the Dandaragan Trough, the Carnac Formation was observed in the Gingin Brook and Moora lines (Moncrieff 1989). In Moora Line bores ML4 and ML3, the shale (including the basal Otorowiri Formation) is about 520 m thick. In Watheroo Line bore ML5, the shale sequence (termed Yarragadee Unit III) extends from the surface to 390 m depth (Harley 1975).

Along the Gillingarra Line, the sand content within the Carnac Formation increases eastward from about 20 per cent in GL6A to 50 per cent in GL7A (Moncrieff 1989), which may reflect proximity to provenance areas on the Yilgarn Craton. North of Agaton, the portion of sand increases to greater than 50 per cent of the formation with the sand being light grey to grey, fine to coarse grained and some gravel, poorly sorted, angular to subangular, feldspathic and clayey (Barnett 1970a). This lithology reaches a thickness of 435 m in Eneabba Line EL3 where the sequence is also more uniform (Commander 1978), and directly overlies the Otorowiri Formation. Conglomeratic layers are fairly common. The Carnac Formation is about 670 m thick in petroleum wells Warro 1 and 2, north-east of Badgingarra, and monitoring bore Agaton 15.

The Carnac Formation is a lacustrine deposit, possibly with some restricted marine elements as well as containing interspersed deltaic sediments (Backhouse 1986b; Crostella & Backhouse 2000). The sandy sequence is fluvial or deltaic.

The Carnac Formation either directly overlies the Otorowiri Formation, or is separated by a thin sequence of fine- to coarse-grained sandstone (Backhouse 1988), referred to onshore as ‘Undifferentiated Parmelia Group’. Offshore, this is probably the Jervoise Sandstone and it is overlain, possibly disconformably, by the Charlotte Sandstone that is a sequence of thick coarse-grained sand beds.

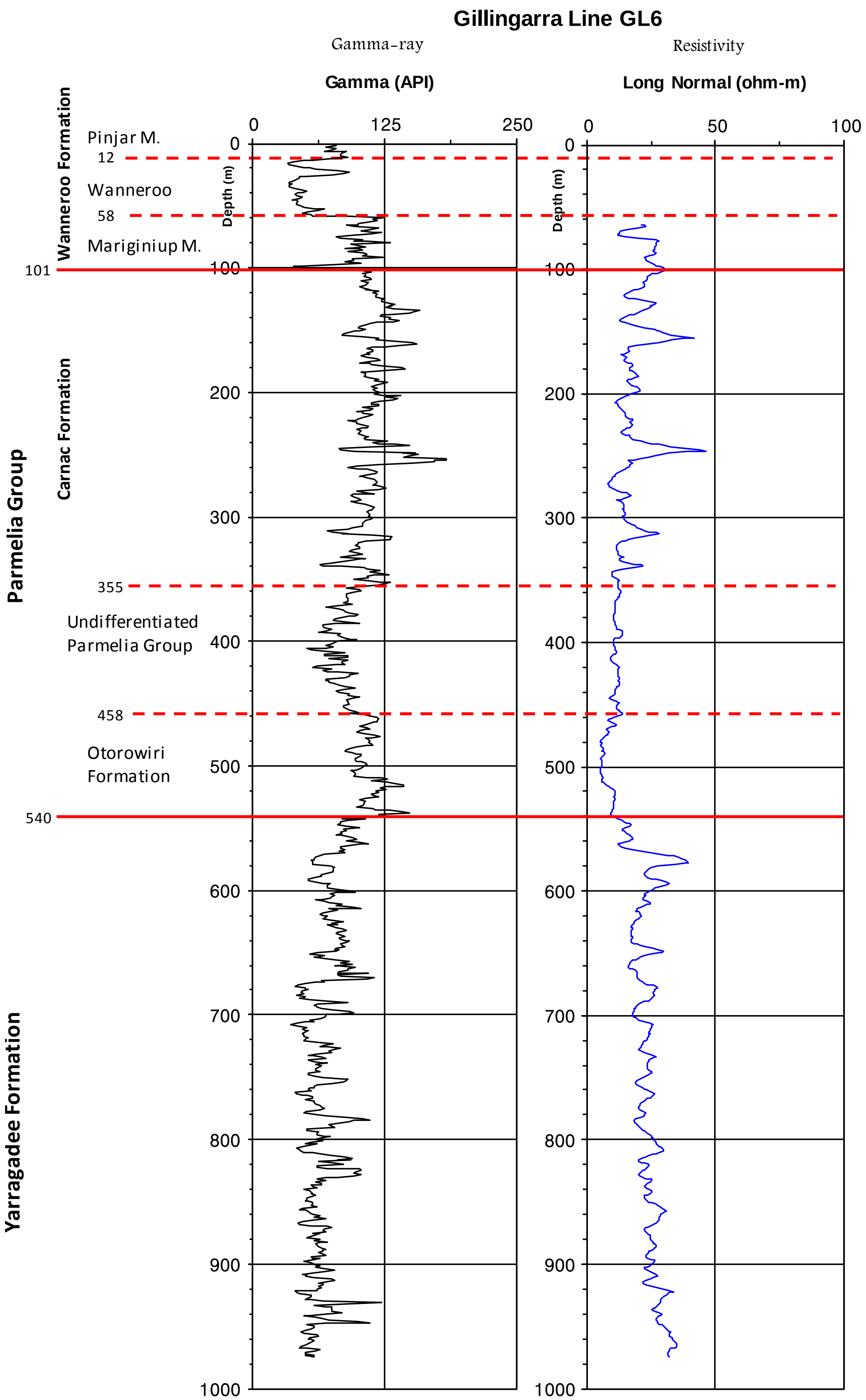


Figure 34 Downhole geophysical log from Gillingarra Line GL6 (0–975 m bgl) showing the Parmelia Group

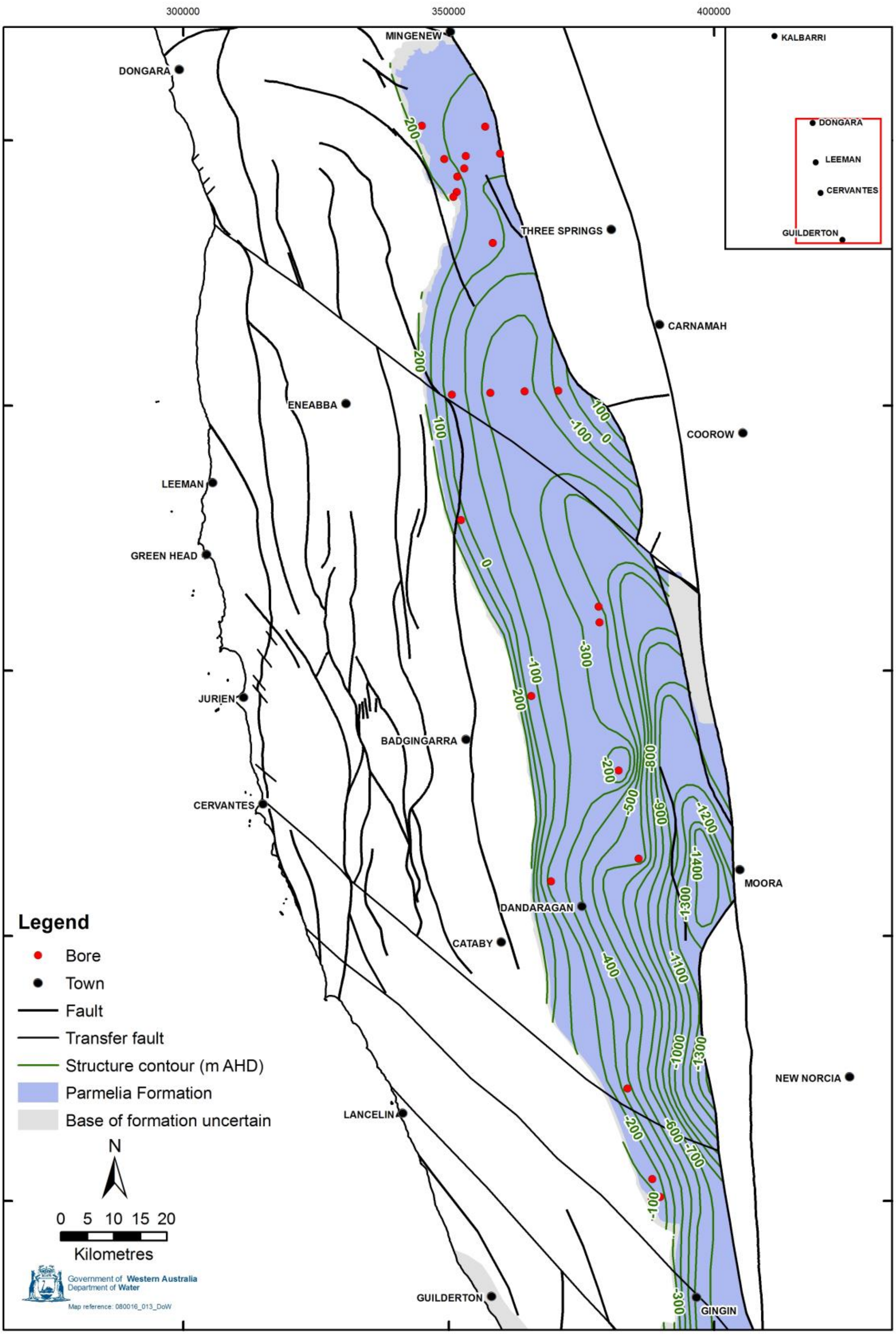


Figure 35 *Parmelia Group: contours on base of unit*

4.18 Warnbro Group

The Warnbro Group is made up of Early Cretaceous sediments that represent sedimentation following the final stage of continental separation from Greater India in the early Neocomian age (Cockbain & Playford 1973). The three formations within the group are the Gage Sandstone, South Perth Shale and Leederville Formation, in ascending order.

Sediments of the Warnbro Group were deposited in non-marine (mainly fluvial) and marine environments associated with a series of marine transgressions. Spring and Newell (1993) identified several depositional sequences in the offshore Vlaming Sub-basin, each representing a marine transgression and deltaic progradation producing a succession of sub-marine fan, deltaic/coastal, and fluvial deposits. Reworked Permian, Triassic and Jurassic palynomorphs are present in increasing abundance towards the west, suggesting rapid erosion of pre-existing strata and that the Beagle Ridge was a major source of sediment (Moncrieff 1989).

The Warnbro Group is present in the southern portion of the Perth Basin, extending northward beneath the coastal plain to near Cataby, and beneath the Dandaragan Plateau to the Watheroo National Park. The Warnbro Group was intersected in all bores of the Gillingarra Line (Moncrieff 1989) and Gingin Brook Line (Sanders 1967a, 1967b), and some bores of the Moora Line (Briese 1979) and Agaton Project (Balleau & Passmore 1972). The thickest intersection was 729 m in Gillingarra Line GL2B with its representative downhole geophysical log being presented in Figure 36. The geophysical log characteristics for each formation and member are discussed in more detail further in this section.

The maximum depth of the Warnbro Group is about –800 m AHD beneath the coastal plain, where it appears to form a north–south syncline east of Guilderton and Lancelin (Figure 37). A similar syncline where the Warnbro Group extends to –300 m AHD is also apparent beneath the Dandaragan Plateau extending north of Gingin. There are minor outcrops of the Warnbro Group in the Dandaragan area.

The Warnbro Group unconformably overlies the Parmelia Group or Yarragadee Formation and was deposited over an irregular pre-existing topography developed during the Neocomian continental breakup. Over most of the northern Perth Basin, the Warnbro Group is unconformably overlain by the mid-Cretaceous Coolyena Group, except in parts of the Swan Coastal Plain, where it is unconformably overlain by the superficial formations.

Gage Sandstone

The Gage Sandstone is the lowermost formation of the Warnbro Group, and was first recognised as a basal sand member of the South Perth Shale by Bozanic (1969). It was upgraded by Davidson (1995), who named it the Gage Formation, but it was subsequently renamed the Gage Sandstone by Crostella and Backhouse (2000) to reflect the arenaceous nature of the unit. The type section is between 1587 and 1704 m depth in petroleum well Gage Roads No. 1 within the Vlaming Sub-basin (MGA Zone 50, 346907 m E, 6463448 m N) (Crostella & Backhouse 2000).

The Gage Sandstone consists of sandstone interbedded with up to 50 per cent siltstone and shale. The sandstone is pale grey, fine grained to granular, poorly to well sorted, angular to subrounded quartz, and contains some feldspar, with minor pyrite and garnet. The shale and siltstone are pale grey, grey and grey brown, and can be micaceous. Deposition was in topographically low areas as basin fan deposits upon the breakup unconformity (Spring & Newell 1993) in a restricted marine environment (Crostella & Backhouse 2000). Microplankton palynology from the Gage Sandstone are of the *Gagiella mutabilis* miospore zone, which indicate a Valanginian age, possibly early Valanginian, of the Early Cretaceous epoch (Moncrieff 1989; Crostella & Backhouse 2000).

The formation unconformably overlies the Parmelia Group or Yarragadee Formation, and is overlain conformably by the South Perth Shale. Downhole gamma-ray logs over the formation show a low gamma-ray count through the sand units, and typically increasing resistivity values from below the South Perth Shale (Figure 36).

The Gage Sandstone has a maximum thickness of about 260 m in North Gingin borehole NGG1A north of Guilderton (Tuffs 2016). However, without palynology, the basal contact with the underlying Yarragadee Formation can be difficult to identify, given the similar lithology. The onshore portion of Gage Sandstone is restricted to beneath the coastal plain, extending north to near Namming Lake (Figure 38). The maximum depth of the Gage Sandstone is about –800 m AHD inland of Guilderton and Lancelin.

South Perth Shale

The South Perth Shale is dominantly marine shale and siltstone within the lower portion of the Warnbro Group (Playford et al. 1976). The type section is between 498 and 567 m depth in South Perth No. 1 (MGA Zone 50, 391492 m E, 6460971 m N).

The formation consists mainly of thinly bedded, grey, brown-black or black siltstone and shale, with minor thin sandy and calcareous beds. The formation is slightly micaceous, glauconitic in parts, and commonly contains minor pyrite (Allen 1978; Moncrieff 1989).

The South Perth Shale was deposited in a distal deltaic to shallow marine environment (Spring & Newell 1993). Palynological assemblages described within the South Perth Shale are assigned to the *G. mutabilis* to *Phoberocysta lowryi* microplankton zones and the *Balmeiopsis limbata* miospore zone (Moncrieff 1989), making it Valanginian to Hauterivian age (Moncrieff 1989; Cockbain 1990; Crostella & Backhouse 2000).

The South Perth Shale is present beneath the coastal plain south of Nilgen Swamp but does not appear to occur east of the Gingin Scarp (Figure 39). The average intersected thickness of the South Perth Shale in the northern Perth Basin is about 64 m, with a maximum of 178 m in Gillingarra Line bore GL3A. The maximum depth of the formation is about –780 m AHD within the north–south depression east of Guilderton and Lancelin, and it shallows towards its northern, western and eastern extent.

The South Perth Shale conformably overlies the Gage Sandstone, or unconformably overlies the Yarragadee Formation, and is overlain conformably by the Leederville Formation. Downhole gamma-ray logs of the formation have a distinctive, relatively uniform high count and corresponding low resistivity over the shale-dominated portions, while the siltstone portions have a higher resistivity.

Leederville Formation

The Leederville Formation is an Early Cretaceous non-marine and marine sequence of interbedded sand and shale overlying the South Perth Shale. The formation was originally introduced as the Leederville Sandstone (Fairbridge 1953) but later redefined as the Leederville Formation (Cockbain & Playford 1973). The type section is in the Leederville Valley (Redan Street) bore between 198 and 433 m depth (MGA Zone 50, 390044 m E, 6466222 m N). In the Perth region, three distinct member units have been defined within the Leederville Formation by Davidson (1995), which are, in ascending order, the Mariginiup, Wanneroo and Pinjar Members.

The Leederville Formation comprises discontinuous, interbedded shale, clayey sandstone and sandstone. The sandstone is light to medium grey, weakly to moderately consolidated, very fine to very coarse grained, angular to subangular, mostly poorly sorted, frequently clayey, and contains variable amounts of angular feldspar. Some intervals of predominantly sandstone are up to about 40 m thick, but they are generally less than 10 m thick. Siltstone, claystone and shales are laminated or thinly bedded, medium grey and brown-grey to black, weakly to well consolidated, and slightly micaceous. Glauconite is present within some marine beds, while there is minor pyrite, carbonaceous material and lignite with the non-marine beds (Cockbain & Playford 1973; Allen 1979; Moncrieff 1989). The bedding is lenticular so that correlation of beds between distant bores is not possible (Briese 1979).

Sediments of the Leederville Formation were deposited in a fluvio–deltaic environment, with shallow marine intervals. Palynological assemblages are from marine and non-marine (dominantly fluvial) environments. Spores and pollen belong to the *B. limbata* miospore zone (Backhouse 1988; Moncrieff 1989) and microplankton of the *Aprobolocysta alata*, *Batioladinium jaegeri*, and *Fromea monilifera* zones are frequently present (Backhouse 1988; Crostella & Backhouse 2000), indicating a Valanginian to earliest Aptian age (Moncrieff 1989).

The Leederville Formation is the most extensive formation of the Warnbro Group, extending beneath the Swan Coastal Plain almost as far north as Cataby, and beneath the Dandaragan Plateau as far north as the Watheroo area (Figure 40). The Leederville Formation has an average thickness of 235 m in fully penetrating drill holes. The greatest thickness of 640 m was intersected to the east of Lancelin in Gillingarra Line GL2B. There are only minor outcrops of the Leederville Formation along the Moore River near Gillingarra Line GL6. The sediments of the Leederville Formation onlap the Yilgarn Craton adjacent to the basin, where they overlie crystalline Archean–Proterozoic basement, and probably underlie the town of Moora (Deshon 2001).

The Leederville Formation conformably overlies the South Perth Shale or Gage Sandstone, or unconformably overlies the Parmelia Group or Yarragadee Formation. It is unconformably overlain by the Osborne Formation (Henley Sandstone and Kardinya Shale Members) or superficial formations (beneath the eastern portion of the coastal plain).

Mariginiup Member

The Mariginiup Member is the basal unit of the Leederville Formation, representing a transitional period between the South Perth Shale and Wanneroo Member. The type section is in Artesian Monitoring AM24 (MGA Zone 50, 389763 m E, 6491300 m N) in the Perth metropolitan area between 423 and 507 m depth (Davidson 1995).

The Mariginiup Member is predominantly of marine origin, and consists of thinly interbedded siltstones and shales with very thin beds of fine-grained sandstone (Davidson 1995). The fine-grained sandstone beds are commonly glauconitic and micaceous. A sandstone bed is apparent within the basal portion of the member that is about 40 m thick and possibly up to 100 m thick in Gillingarra Line GL2B. This sandstone bed consists of fine to very coarse grained sandstone and gravel with fine pebbles, poorly to well sorted, subangular to rounded, and feldspathic.

Microplankton ranging from the *G. mutabilis* to *Aprobolocysta* zones are present within the Mariginiup Member, suggesting Valanginian to early Barremian age (Backhouse 1980).

The Mariginiup Member is recognised in downhole geophysical logs as having a high gamma-ray count centred around 100–125 API with low gamma count intervals between 75 and 100 API corresponding with the sand beds (Figure 36). The basal portion has a predominantly low gamma-ray count corresponding to the basal sand. This provides a sharp contrast with the underlying high gamma-ray count of the South Perth Shale.

Wanneroo Member

The Wanneroo Member comprises a mainly non-marine sandstone sequence overlying the Mariginiup Member. The type section is within Artesian Monitoring AM24 (MGA Zone 50, 389763 m E, 6491300 m N) in the Perth metropolitan region from 223 to 423 m depth. The Wanneroo Member is late Neocomian to Aptian age (Backhouse 1980).

The Wanneroo Member contains weakly consolidated sandstone beds between 12 and 15 m thick with minor beds of siltstone and shale (Davidson 1995). The sandstone is pale grey and consists of fine to very coarse grained (predominantly coarse), poorly sorted, angular to subangular quartz grains. The siltstone and shale are grey and slightly micaceous. Granitic boulders are common near the Darling Scarp.

In downhole geophysical logs, the Wanneroo Member is characterised by a relatively low gamma-ray count of below 50 API over the sandstone beds.

Pinjar Member

The Pinjar Member is the uppermost unit of the Leederville Formation and consists of discontinuous, interbedded sandstone, siltstone and shale of marine and non-marine origin. The type section is from 157 to 223 m depth in Artesian Monitoring bore AM24 in the Perth metropolitan area (MGA Zone 50, 389763 m E, 6491300 m N) (Davidson 1995). The Pinjar Member extends northward to near Lancelin and has a maximum onshore thickness of about 150 m (Davidson 1995).

The Pinjar Member can comprise up to 50 per cent sandstone (Moncrieff 1989), with sandstone beds up to several metres thick. The sandstone is grey, weakly consolidated and consists of poorly sorted, fine to very coarse, subangular to subrounded quartz grains. The siltstone and shale are dark grey to black and micaceous, with thin laminations of fine-grained sandstone and minor lignite fragments. However, the upper 40 m of the Pinjar Member in the western portion of the Gillingarra Line (GL1, GL2, GL3) is characterised by a dark greenish grey to greenish black, slightly clayey, sandy, glauconitic siltstone and silty sandstone while the sand is very fine to fine grained, subrounded to rounded and well sorted.

In downhole geophysical logs, the Pinjar Member is characterised by a relatively high gamma-ray count centred around 100 API where it is shaley providing a contact with the lower count associated with the Wanneroo Member (Figure 36).

Downhole geophysical logs have thin zones of low gamma-ray count across sandstone intervals with higher counts in siltstone and shale beds.

The upper Pinjar Member within the western portion of the Gillingarra Line is a shallow marine deposit (Moncrieff 1989) corresponding to the *B. jaegeri* to *F. monilifera* zones, being late Neocomian to Aptian age (Backhouse 1980).

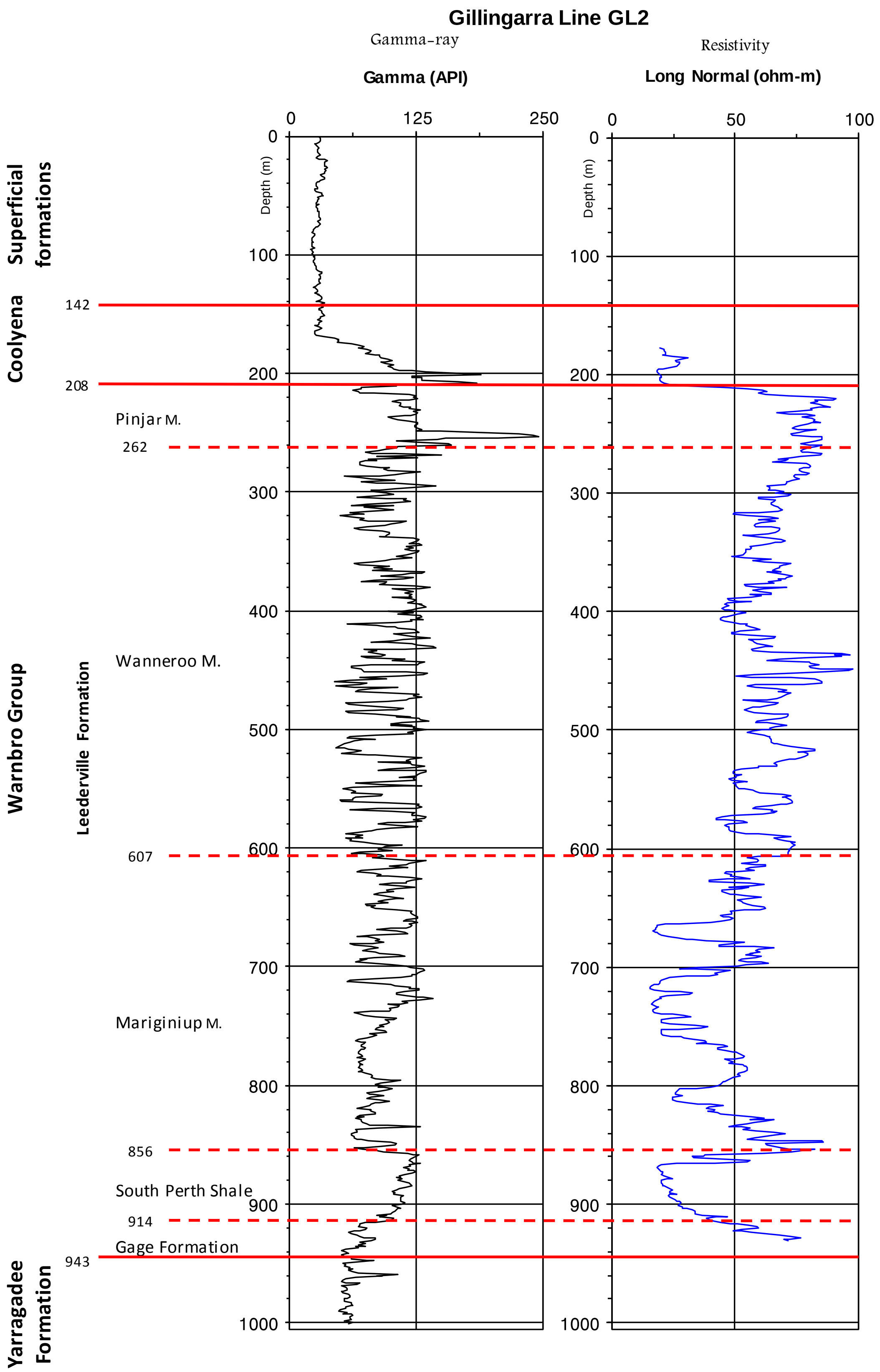


Figure 36 Downhole geophysical log from Gillingarra Line 2B (0–1000 m bgl) showing the Warnbro Group

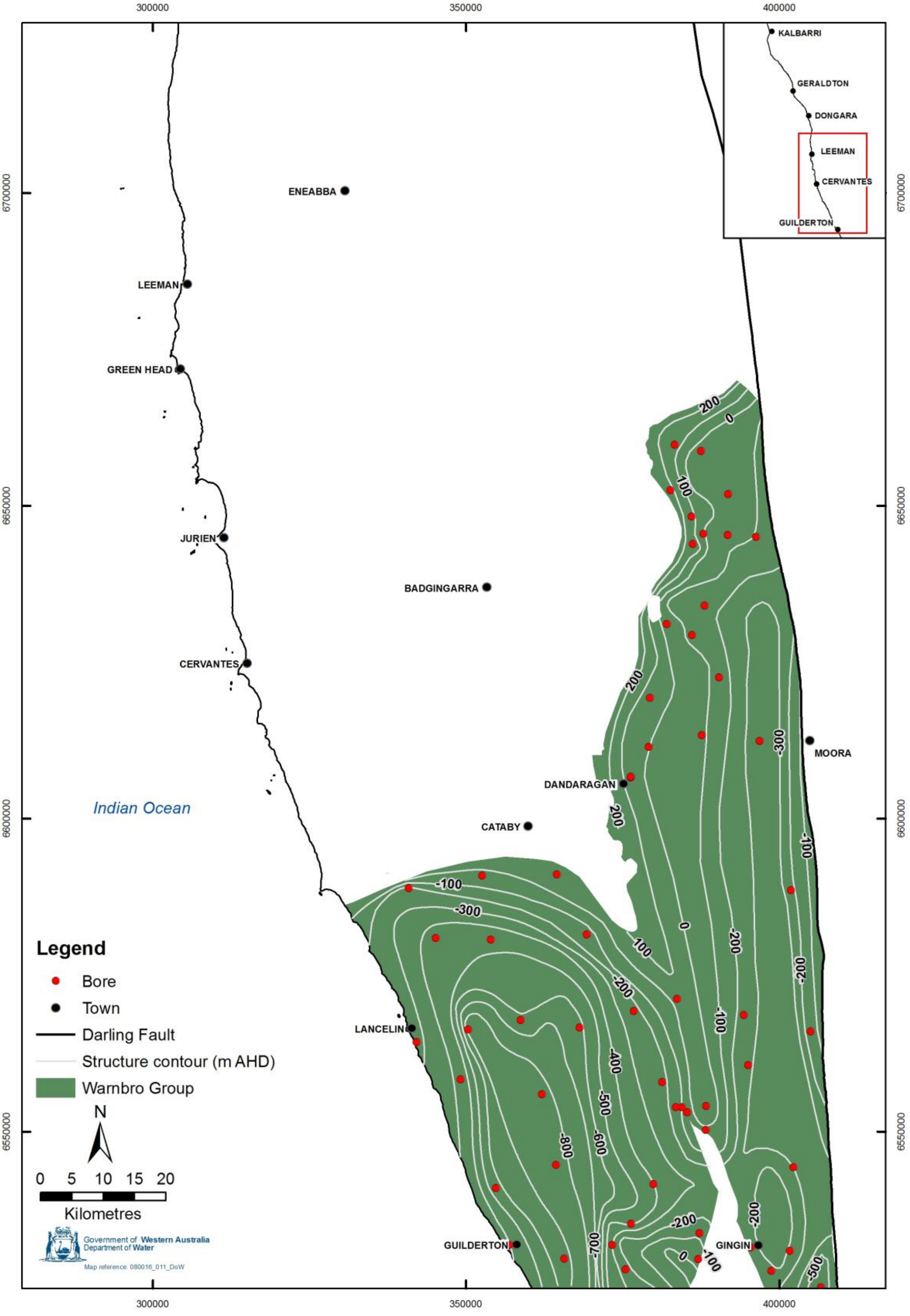


Figure 37 Warnbro Group: contours on base of unit

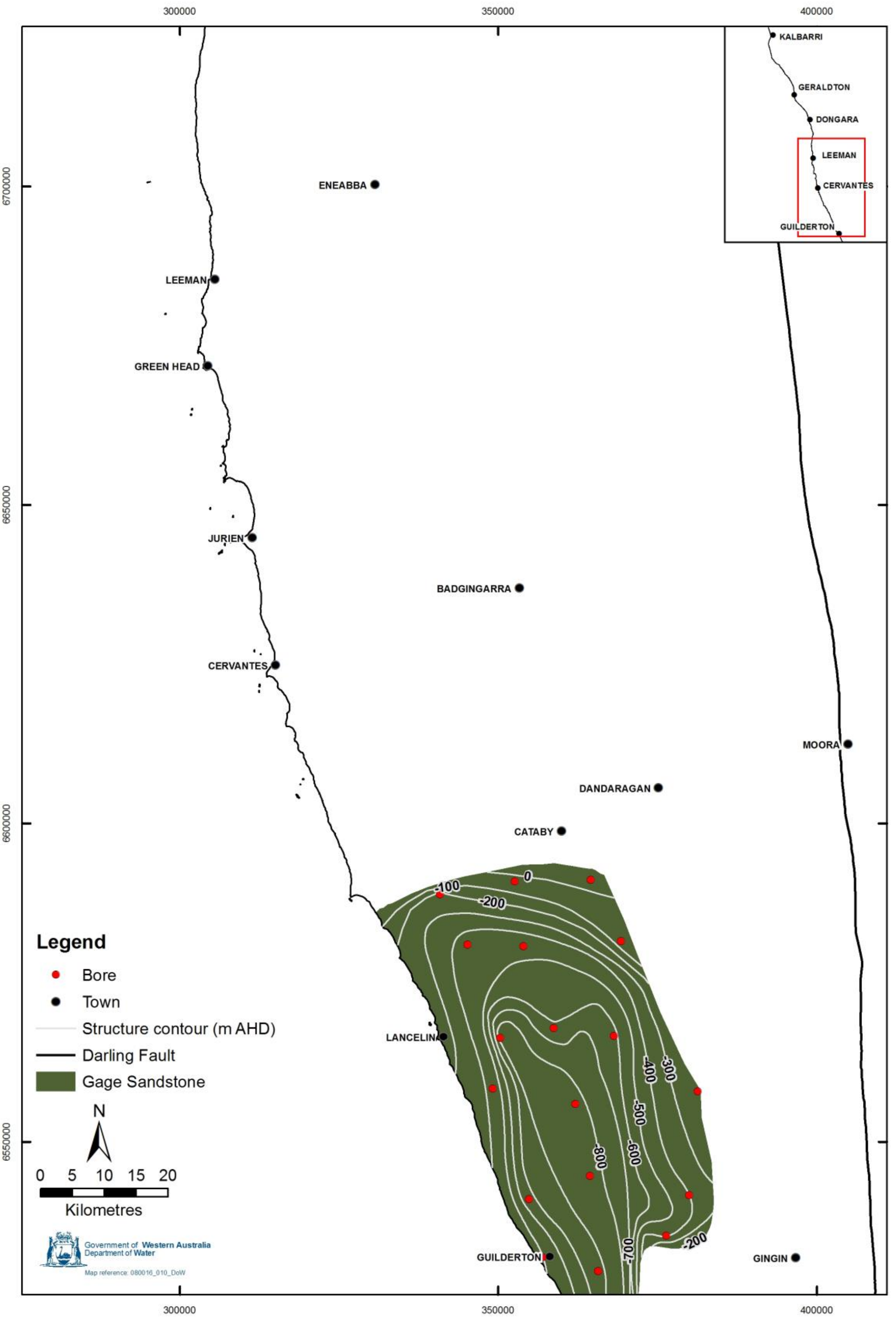


Figure 38 Gage Sandstone: contours on base of unit

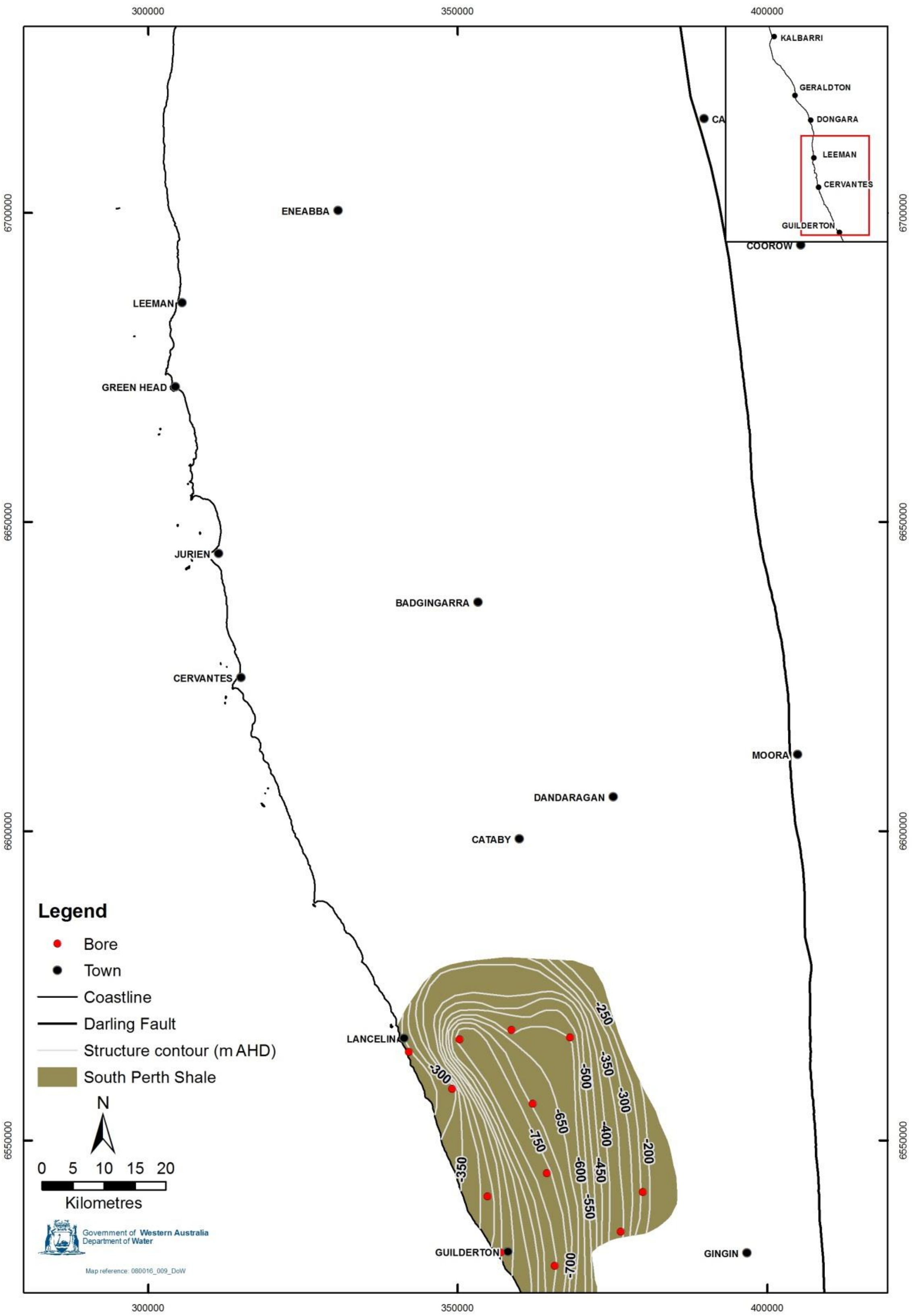


Figure 39 South Perth Shale: contours on base of unit

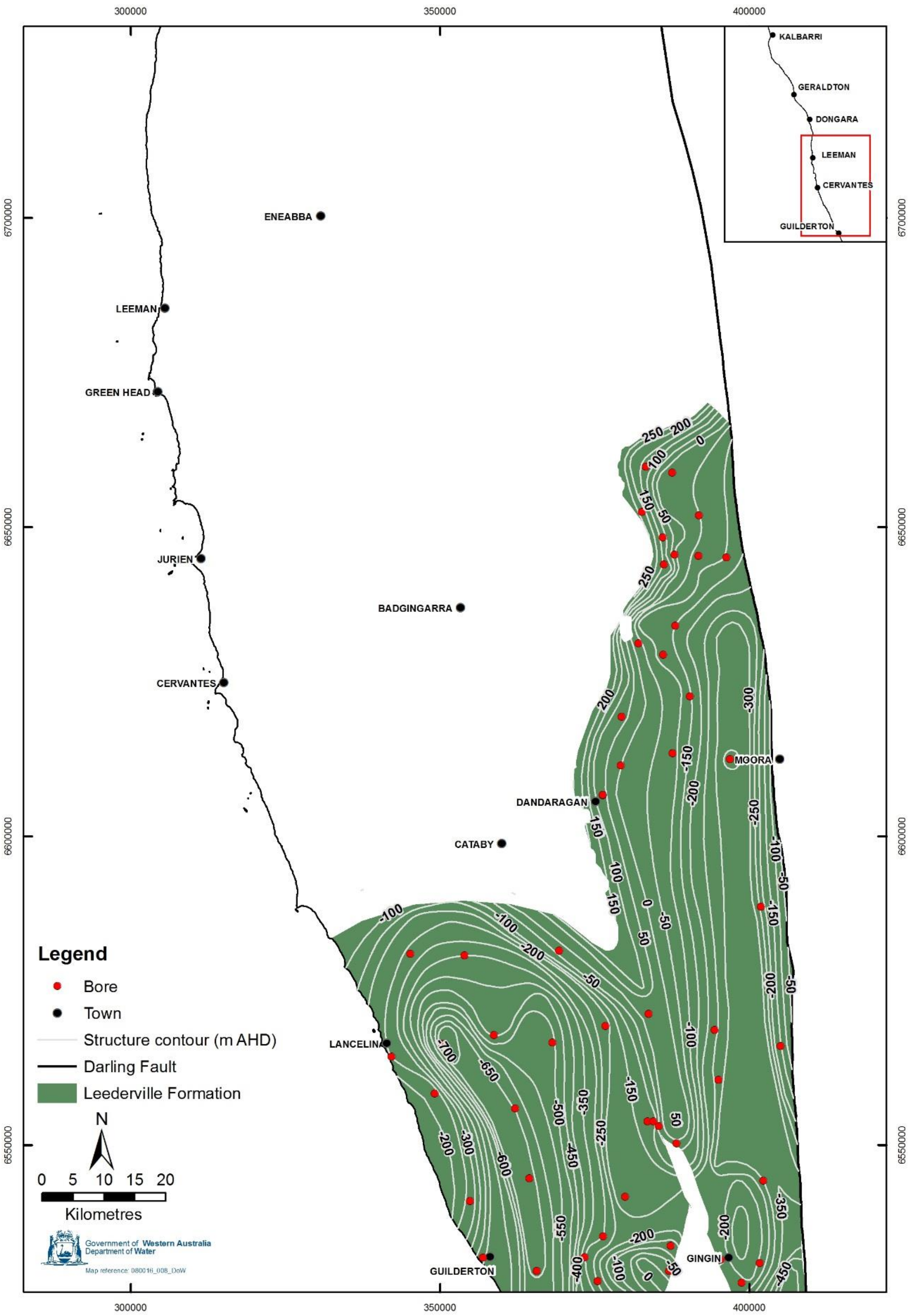


Figure 40 Leederville Formation: contours on base of unit

4.19 Winning Group

The Winning Group is a Cretaceous marine sequence within the Carnarvon Basin that was deposited during a major transgression throughout most of the Early Cretaceous, and is a time equivalent of the Warnbro Group. The Winning Group was originally named the 'Winning Series' by Raggat (1936), but was later amended to the 'Winning Group' by Fairbridge (1953). In the southern part of the Carnarvon Basin, the Winning Group consists of, in ascending order: the Birdrong Sandstone, Muderong Shale, Windalia Radiolarite, Alinga Formation and Gearle Siltstone (Mory et al. 2005; Hocking & Mory 2006) (see Table 8).

The Birdrong Sandstone is a basal sand facies comprising a fine to coarse grained, quartzose, commonly glauconitic, friable and often silty sandstone, with some silty claystone and shale. It is typically pale grey to white, and locally greenish. The Birdrong Sandstone is a coastal to near-shore deposit that was laid down with the marine transgression.

The Muderong Shale is an argillaceous sequence which lies conformably between the Birdrong Sandstone and the Windalia Radiolarite. The Windalia Sandstone Member was initially thought to occur within the Windalia Radiolarite, but is now recognised as belonging in the upper part of the Muderong Shale.

The Windalia Radiolarite is a radiolarian siltstone with a radiolarian content of up to 70 per cent. It lies conformably between the Muderong Shale below and Alinga Formation above.

The Alinga Formation is a glauconitic claystone and siltstone sequence, which outcrops near the lower Murchison Riverand and grades laterally into the Gearle Siltstone further north (Hocking et al. 1987). It rest conformably on the Windalia Radiolarite and is disconformably overlain by the Gearle Siltstone.

The Gearle Siltstone is a silty and clayey formation, with radiolarian siltstone, which unconformably overlies the Alinga Formation and is conformably overlain by the Haycock Marl.

The Winning Group has an outcrop area of about 900 km^2 south of the Murchison River and extends about 40 km south of Kalbarri. There is little borehole data available for the Winning Group, which has only been intersected in a few private bores. Drillers' logs from these bores indicate about 9 m of clay and 6 m of sand with an 'overburden' up to 27 m thick, which is likely to be weathered Winning Group. The lower sand unit may belong to the Birdrong Sandstone. The maximum thickness of the Winning Group south of the Murchison River is probably less than 100 m, preserved as remnant hills, and is typically less than 40 m thick.

The Winning Group unconformably overlies the Wittecarra Sandstone or Tumblagooda Sandstone to the south of the Murchison River. At its southern limit, the Cattamarra Coal Measures and Kockatea Shale may interfinger between the Winning Group and Tumblagooda Sandstone. The group has been fully eroded along the Murchison River, exposing the underlying Tumblagooda Sandstone. Minor patches of Toolonga Calcilutite overlie the Winning Group towards the west.

4.20 Coolyena Group

The Coolyena Group is a series of mid-Cretaceous marine formations comprising shale, glauconitic greensands and chalk. The Coolyena Group was originally defined by Cockbain and Playford (1973) and later extended by Davidson (1995). It includes, in ascending order: the Osborne Formation, Molecap Greensand, Gingin Chalk, and Poison Hill Greensand on the Dandaragan Plateau (Table 6). However, on the Swan Coastal Plain, the latter three formations are undistinguished and assigned to the Lancelin Formation. Three members are distinguished in the Osborne Formation and they are (in ascending order) the Hensley Sandstone, Kardinya Shale and Mirrabooka members.

The Coolyena Group was deposited under shallow marine conditions during a period of tectonic stability and is Albian to Maastrichtian in age (Early to Late Cretaceous period). The sediments comprise shale, greensand, and chalk and marl. The Coolyena Group has a maximum intersected thickness of 192 m within Agaton 13 (Balleau & Passmore 1972), but is generally less than 150 m thick (Moncrieff 1989).

In the northern Perth Basin, the extent of the Coolyena Group is restricted to two distinct areas: beneath the Swan Coastal Plain as far north as Lancelin, and beneath the Dandaragan Plateau extending north to the Watheroo National Park (Figure 42). The Coolyena Group unconformably overlies the Warnbro Group and is unconformably overlain by the superficial formations beneath the coastal plain. There are minor outcrops of the Coolyena Group in the Dandaragan area, east of the Dandaragan Scarp (Carter & Lipple 1982). Structure contours at the base of the Coolyena Group are presented in Figure 42.

The geophysical logs are highly variable in the Coolyena Group, with high gamma-ray counts in the shaley Kardinya Shale Member of the Osborne Formation and low gamma ray counts in the Henley Sandstone and Mirrabooka members (Figure 41). The geophysical log characteristics for each formation and relevant member are discussed in more detail further in this section.

Osborne Formation

The Osborne Formation comprises marine deposits of weakly to well consolidated, dark greenish grey, glauconitic shale, siltstone, and silty and clayey sandstone, and is the basal unit of the Coolyena Group (McWhae et al. 1958; Davidson 1995). The type section is between 37 and 133 m depth in King Edward Street bore in the Perth metropolitan area (MGA Zone 50 388242 m E, 6470176 m N). Three member units are recognised, which are, in ascending order: the Henley Sandstone Member (a basal sandstone sequence), the Kardinya Shale Member (a middle shale and siltstone unit) and the Mirrabooka Member (an upper, predominantly sandstone sequence).

The presence of glauconite and microplankton in the Osborne Formation indicate deposition in a near-shore, shallow-marine environment. Palynological assemblages belong to the *Pseudoceratium turneri* or *Odontochitina operculata* microplankton zones, and the *Endoceratim ludbrookiae 'c'* microplankton subzone (Moncrieff 1989), which are Late Aptian to Cenomanian age (Cookson & Eisenack 1958; Backhouse 1979, 1980b), equivalent to the Early to Late Cretaceous epoch.

The Osborne Formation is present over two areas, beneath the Swan Coastal Plain and beneath the Dandaragan Plateau. Beneath the western portion of the coastal plain between the Moore River and Eaglehawk Flats (about 13 km north-east of Lancelin), the Osborne Formation was intersected in Gillingarra Line GL2A and GL3A (Moncrieff 1989), and Gingin Brook Line 4 (Sanders 1967a). The formation is deepest in this part of the basin extending to –180 m AHD, and possibly reaching to 0 m AHD about its northern extent. Beneath the Dandaragan Plateau, the Osborne Formation extends as far north as the Watheroo National Park, west of Watheroo. The formation ranges in depth from about –80 m AHD south-east of Gingin to over 220 m AHD north-west of Moora. It was intersected in Gillingarra Line GL7A and GL8A, Moora Line ML1A, and in several of the Agaton bores. The Osborne Formation has been completely eroded between the western and eastern areas. It extends southward into the Perth metropolitan area (Davidson 1995).

The Osborne Formation unconformably overlies the Leederville Formation and is conformably or unconformably overlain by the Molecap Greensand in the east, and is disconformably overlain by the Lancelin Formation in the west. Beneath the central coastal plain, it is unconformably overlain by the superficial formations.

Henley Sandstone Member

The Henley Sandstone Member is the basal unit of the Osborne Formation. The type section is between 229 and 270 m depth in Artesian Monitoring bore AM11 in the Perth metropolitan area (MGA Zone 50, 406614 m E, 6525106 m N) (Davidson 1995). The Henley Sandstone Member was previously referred to as the Dandaragan Sandstone (McWhae et al. 1958) and attributed to the upper portion of the Warnbro Group (Playford et al. 1976), but was later named the Henley Sandstone Member of the Osborne Formation (Davidson 1995).

The Henley Sandstone Member consists of fine to very coarse grained quartz sandstone and fine conglomerate with minor siltstone and claystone. The sands are poorly to moderately sorted, angular to subrounded, and weakly consolidated. The Henley Sandstone Member is characteristically dark greenish brown and glauconitic, becoming feldspathic eastward towards the Yilgarn Craton. The Henley Sandstone Member can sometimes be difficult to distinguish lithologically from the underlying Leederville Formation. Deposition was probably in a high energy, shallow-marine environment (Moncrieff 1989).

In the northern Perth Basin, the Henley Sandstone Member is present beneath the south-western portion of the coastal plain, and beneath the eastern portion of the Dandaragan Plateau (Harley 1974; Briese 1979a; Moncrieff 1989). The basal elevation of the Henley Sandstone Member ranges from 0 to –280 m AHD (Figure 43). The average thickness is about 25 m, with a maximum thickness of 48 m intersected in Red Gully bore RG2A (Diamond 2000).

The Henley Sandstone Member at the base of the Osborne Formation is recognisable by a low gamma-ray count and higher resistivity when compared with the high gamma-ray and low resistivity values of the Kardinya Shale Member (see Figure 41). It can be difficult to distinguish the Henley Sandstone Member from the underlying Leederville Formation without palynology, although it can have a lower gamma-ray count and lack the distinct peaks of the Leederville Formation.

Kardinya Shale Member

The Kardinya Shale Member, a thick siltstone and shale horizon, is the major unit within the Osborne Formation. The type section is within Artesian Monitoring bore AM42 in the Perth metropolitan area between 28 and 167 m (MGA Zone 50, 388123 m E, 6452372 m N) (Davidson 1995). The Kardinya Shale Member outcrops along the Moore River for at least 5 km west of the Darling Fault.

The Kardinya Shale Member consists of moderately to tightly consolidated, interbedded siltstone and shale with minor thin interbeds of fine- to medium-grained sandstone (Diamond 2000). It is dark green to black, carbonaceous, micaceous and glauconitic, particularly towards the base. It contains rare to common pyrite, and is calcareous in parts. Nodules of phosphate were found at the base of the formation in Agaton bore A23 (Balleau & Passmore 1972).

The Kardinya Shale Member is present in the west beneath the coastal plain, and in the east adjacent to the Gingin Scarp (Figure 44). The deepest occurrences are in the western portion, with basal depths from –180 m AHD, rising to –25 m AHD in the north. Within the eastern portion, the basal depth ranges between –40 m AHD in the south to over 200 m AHD in the north. It occupies a north–south elongate trough stretching from Gingin to north of Moora that may represent a pre-existing valley at the time of deposition.

The average intersected thickness of Kardinya Shale Member within the northern Perth Basin is about 80 m, with the thickest intersection of 235 m in Glen Ruff bore GR1, 3 km north-west of Moora Line ML1

The Kardinya Shale Member is recognisable in geophysical logs by its very tight pattern of high gamma-ray count centred between 50 and 100 API and low resistivity due to the high shale content. These characteristic signatures provide sharp contrasts with the Henley Sandstone Member below and Mirrabooka Member above.

Mirrabooka Member

The Mirrabooka Member is a sandstone unit at the top of the Osborne Formation. The type section is between 34 and 199 m depth in Artesian Monitoring bore AM30Z (MGA Zone 50, 397699 m E, 6478981 m N) in the Perth metropolitan area (Davidson 1995). The unit was previously referred to informally as the ‘Channel Sand’ in the Mirrabooka area north-east of Perth (Allen 1977). In some areas, it may be a lateral equivalent of the Kardinya Shale Member (Kay & Diamond 2001), but this relationship is not well understood.

The Mirrabooka Member comprises dark greenish brown, weakly consolidated, fine to very coarse grained sand and gravel that is very poorly to moderately sorted and subangular to well rounded. It is silty and richly glauconitic, containing thin interbeds of dark green to black siltstone and shale. Within the weathering zone, the sandstone is limonitic.

The Mirrabooka Member has only been identified in a few drill holes in the eastern portion of the basin and north of the Moore River (Kay & Diamond 2001). The eastern margin of the Mirrabooka Member appears to have been truncated by the Molecap Greensand. The deepest occurrence is below 0 m AHD near Gingin Brook before rising to about 170 m AHD at its north-eastern limits. The Mirrabooka Member outcrops adjacent to the Darling Fault, west of Wannamal. The average thickness of the Mirrabooka Member is 15 m; however, it can be up to 50 m thick in West Koojan near Dandaragan (HydroConcept 2013) and 40 m thick in Gingin town water supply bore 1/75 (Figure 45).

In geophysical logs, the Mirrabooka Member contrasts with the underlying Kardinya Shale Member owing to its relatively low gamma-ray count and higher resistivity. The Mirrabooka Member is difficult to distinguish from the Molecap Greensand without palynological evidence.

Molecap Greensand, Gingin Chalk, Poison Hill Greensand and Lancelin Formation

The Molecap Greensand, Gingin Chalk, Poison Hill Greensand and Lancelin Formation form a sequence of Late Cretaceous shallow marine deposits comprising glauconitic sandstone with fossiliferous chalk and marl units. Moncrieff (1989) defined this sequence as the Lancelin Formation with each formation being member units; however, this nomenclature is not adopted in this bulletin because the Lancelin Formation, present in the west and central portion of the Swan Coastal Plain, is age equivalent to the Molecap Greensand, Gingin Chalk and Poison Hill Greensand, which are present beneath the Dandaragan Plateau (see Table 6).

Downhole gamma-ray logs for the Molecap Greensand and Poison Hill Greensand typically have relatively low gamma-ray count with slightly higher count across the clay portions. However, the response is markedly lower than those observed for the Kardinya Shale Member and clay intervals in the Leederville Formation. Intervals of chalk and marl have a very low gamma-ray response.

Palynology suggests a near-shore marine depositional environment, and Turonian to Campanian age, which may extend to the Maastrichtian age, of the Late Cretaceous period (Wilde & Low 1978; Rexilius 1984; Backhouse 1986a; Moncrieff 1989; Cockbain 1990; Davidson 1995).

The distribution of these deposits is similar to the Osborne Formation with two separate areas: in the south-west beneath the Swan Coastal Plain, and in the south-east beneath the Dandaragan Plateau (Figure 46). Beneath the coastal plain, the base of the sequence extends from below –110 m AHD near Guilderton to about 0 m AHD along its northern and eastern extent. Beneath the Dandaragan Plateau, they are present at higher elevations than in the west, rising from about 20 m AHD at Gingin to about 300 m AHD in the north. They are thickest beneath the central portion of the Dandaragan Plateau, north of the Moore River, and may be up to 150 m thick east of Yallalie; however, this may include the Mirrabooka Member of the Osborne Formation that can be difficult to distinguish from the Molecap Greensand.

Molecap Greensand

The Molecap Greensand is a shallow marine deposit from the Late Cretaceous that was originally defined by Fairbridge (1953). The type section is in the greensand quarry on Molecap Hill (MGA Zone 50, 347970 m E, 6528792 m N), 2 km south of Gingin.

Typically, the Molecap Greensand comprises greenish grey-brown, very fine to medium and coarse grained, poorly to moderately sorted, subangular to well rounded, unconsolidated quartz sand. It contains abundant (5–10%) glauconite (Moncrieff 1989) with intervals of sandy clay. Thin beds of phosphatic nodules are present within the upper and lower portion of the formation in the Dandaragan area (Matheson 1948). Phosphatised wood is also common. When weathered, the glauconite is altered to limonite, and the formation is yellow, yellow-brown and brown through to a deep red-brown in outcrop.

The Molecap Greensand predominantly overlies (conformably) the Mirrabooka Member of the Osborne Formation, but beneath the western portion of the Dandaragan Plateau, it unconformably overlies the Leederville Formation. The Molecap Greensand is overlain conformably by the Gingin Chalk, or where the chalk is absent, it is unconformably overlain by the Poison Hill Greensand.

Ichthyosaur and plesiosaur bones have been collected from the formation (Teichert & Matheson 1944), and pelecypods and belemnites were observed at Gingin. Microplankton indicate that the Molecap Greensand is Turonian to Santonian in age (Davidson 1995). The Haycock Marl (argillaceous calcilutite and marl) of the Carnarvon Basin is most likely an age equivalent of the Molecap Greensand (Table 8). Hocking and Mory (2006) mentioned the presence of the Haycock Marl above the Gearle Siltstone in the Kalbarri area.

Gingin Chalk

The Gingin Chalk is a shallow marine deposit of the Late Cretaceous (Carter & Lipple 1982; Moncrieff 1989; Cockbain 1990) that was originally named by Glauert (1910). The type section is 18.9 m thick where it outcrops in McIntyres Gully, 1.6 km north of Gingin (MGA Zone 50, 395472 m E, 6534917 m N). The Gingin Chalk outcrops just north of Gingin and within Caren Caren Brook to the south of Dandaragan.

The Gingin Chalk consists of weakly to moderately consolidated chalk that is pale grey to whitish green, and is slightly glauconitic. In some areas, thin greensand beds are present that can be very difficult to distinguish from the underlying Molecap Greensand (Wilde & Low 1978). It is highly fossiliferous, containing coccoliths, foraminifera, brachiopods, molluscs, cirripedes, echinoids and crinoids, indicating a Santonian to Campanian age (Cockbain 1990).

The Gingin Chalk is present upon the southern Dandaragan Plateau, where it thins to the north and becomes sandier. Equivalent chalk units are present beneath the coastal plain in the west, where they are included into the Lancelin Formation. The formation is lenticular, and may be absent in places (Carter & Lipple 1982). The Gingin Chalk conformably overlies the Molecap Greensand or unconformably overlies the Osborne Formation (Davidson 1995) and is conformably overlain by the Poison Hill Greensand.

Toolonga Calcilutite

The Toolonga Calcilutite is a calcareous deep marine (pelagic) deposit in the Carnarvon Basin (Hocking et al. 1987) that was originally named by Johnstone et al. (1958) (Table 8). The type section near Kalbarri is 2 km north of the Yalthoo bore on Murchison House Station (Hocking et al. 1982). It is a massive, fine-grained, calcareous and fossiliferous deposit, usually containing some glauconite, with phosphate nodules locally present at the base and top of the unit (Hocking et al. 1982). It is greenish grey to white in weathered outcrop (Hocking et al. 1982; Hocking et al. 1987).

The distribution of the Toolonga Calcilutite is restricted to south of the Murchison River with very minor, thin deposits to the west of the Northampton Inlier, where it is disconformable upon the Winning Group (Hocking et al. 1982; Hocking et al. 1987). Abundant foraminifera suggest a Santonian to Campanian age (85.8 – 70.6 Ma) (Belford 1958), making it a time equivalent of the Gingin Chalk in the Perth Basin.

Poison Hill Greensand

The Poison Hill Greensand is a near-shore marine deposit that was named by Fairbridge (1953) for a sequence of greensand overlying the Gingin Chalk. The type section is in a bore at Poison Hill (MGA Zone 50, 393867 m E, 6536749 m N), about 7.5 km north–northwest of Gingin. The type section is 23 m thick but the maximum thickness probably exceeds 41 m in the subsurface (Wilde & Low 1978). Beneath the coastal plain, the upper portion of the Lancelin Formation is considered equivalent to the Poison Hill Greensand (Cockbain 1990; Davidson 1995).

The Poison Hill Greensand is similar to the Molecap Greensand in appearance, consisting of glauconitic sandstone with thin beds of dark grey-green to black glauconitic clay. The sands are unconsolidated, very fine to very coarse grained, poorly sorted, subrounded to rounded, silty and locally clayey (Playford, et al. 1976; Moncrieff 1989). Within the lower portion, the sand is very fine to medium grained and becomes coarse to very coarse grained in upper parts (Playford, et al. 1976). The sand is yellowish brown to greenish grey. In outcrop, the formation is often highly lateritised. Microplankton palynology suggests Campanian to Maastrichtian age (Playford et al. 1976; Cockbain 1990).

The Poison Hill Greensand rests conformably on the Gingin Chalk beneath the southern portion of the Dandaragan Trough and extends as far north as Watheroo. It is unconformably overlain by surficial deposits on the Dandaragan Plateau. The Poison Hill Greensand is at least 40 m thick in the Dandaragan area (Low 1965). Outcrops of Poison Hill Greensand are present from Gingin to Badgingarra (Playford et al. 1976).

Poison Hill Greensand is unconformably overlain by superficial formations on the Swan Coastal Plain in the Perth region (Davidson 1995); however, it seems it has not been identified north of AM3.

Lancelin Formation

The type section for the Lancelin Formation is between 32 and 46 m depth within Lancelin No. 2B bore (MGA Zone 50, 340068 m E, 6561938 m N), near the Lancelin township. It was previously referred to as the Lancelin Beds (Edgell 1964).

The Lancelin Formation is of marine origin comprising white, light grey to greenish brown marl with some glauconitic lenses, chalk and calcareous mudstone. It has a similar lithology to the Gingin Chalk. Wilde and Low (1978) suggested it is younger than the Gingin Chalk based on palynology, which indicates a Coniacian to late Maastrichtian age (Backhouse 1986b; Rexilius 1984).

The Lancelin Formation is present beneath the western and central portion of the coastal plain extending north to about 9 km north of the Gillingarra Line. It is an equivalent of the Poison Hill Greensand (Davidson 1995) and Gingin Chalk, and also possibly part of the Molecap Greensand (Cockbain 1990). Davidson (1995) described the formation as conformably overlying the Gingin Chalk. However, it is more likely to be conformably overlying the Molecap Greensand, or disconformably overlying the Osborne Formation. It is unconformably overlain by the superficial formations.

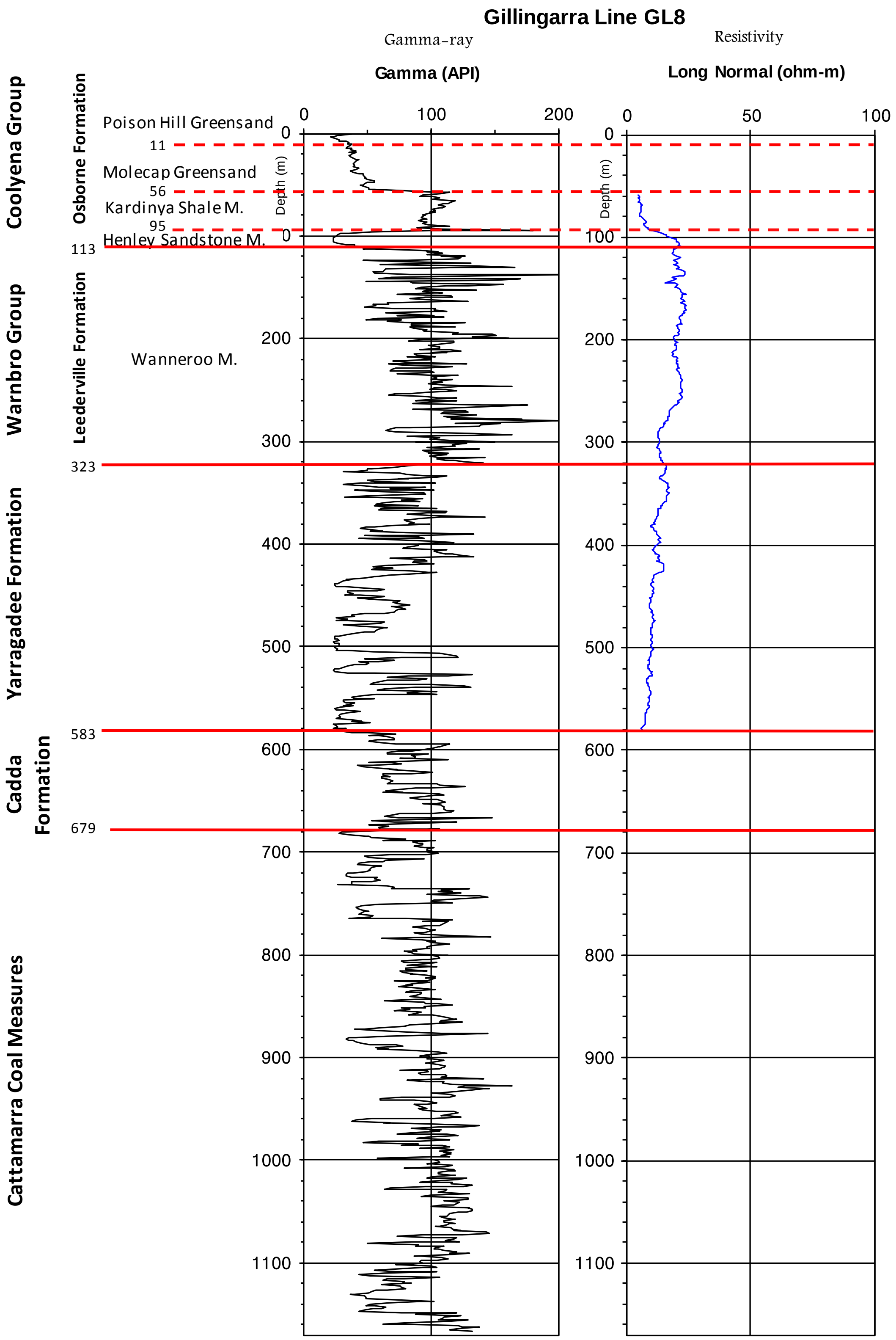


Figure 41 *Downhole geophysical log from Gillingarra Line GL8 (0–1170 m bgl) showing the Coolyena Group*

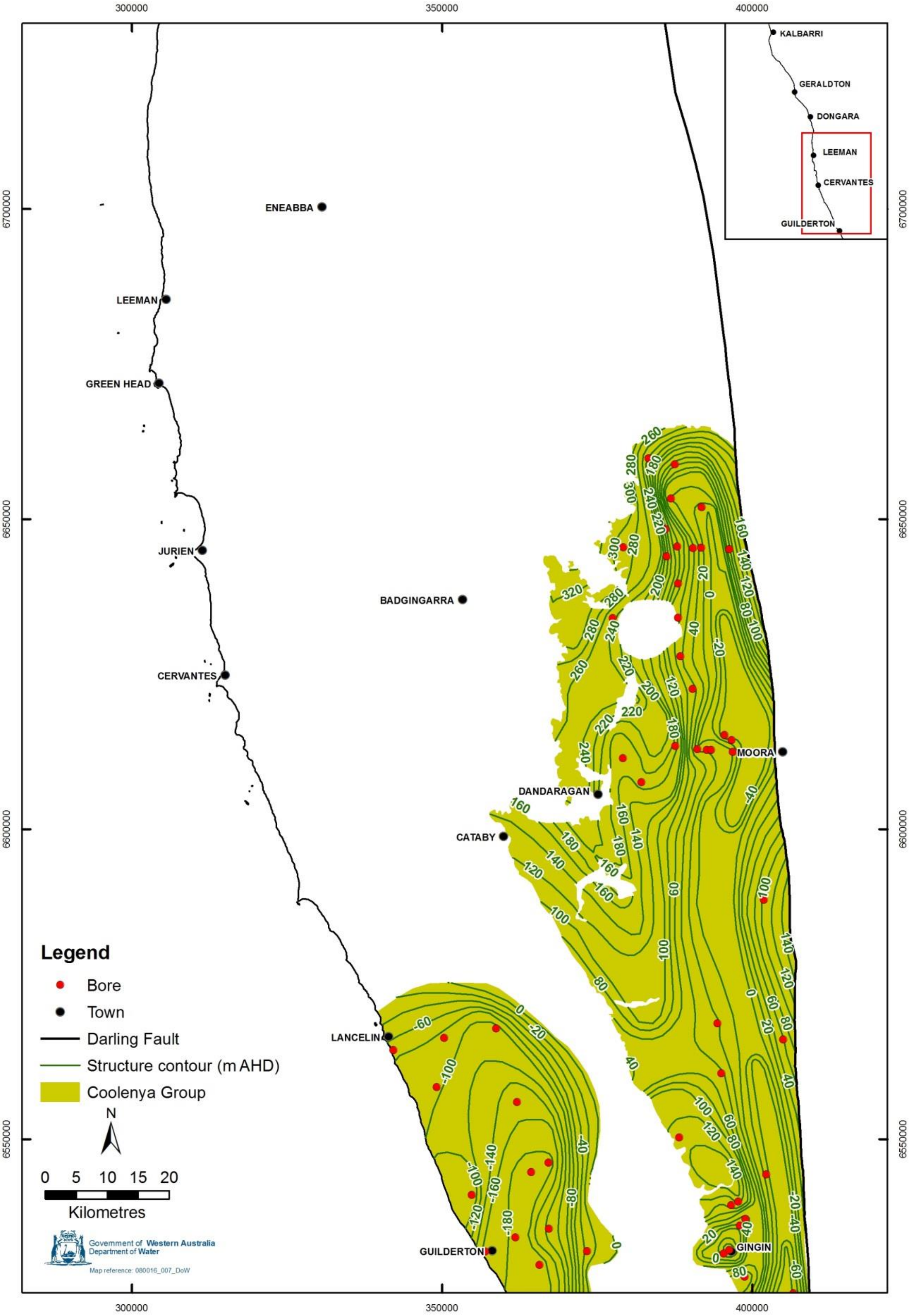


Figure 42 Coolyena Group: contours on base of unit

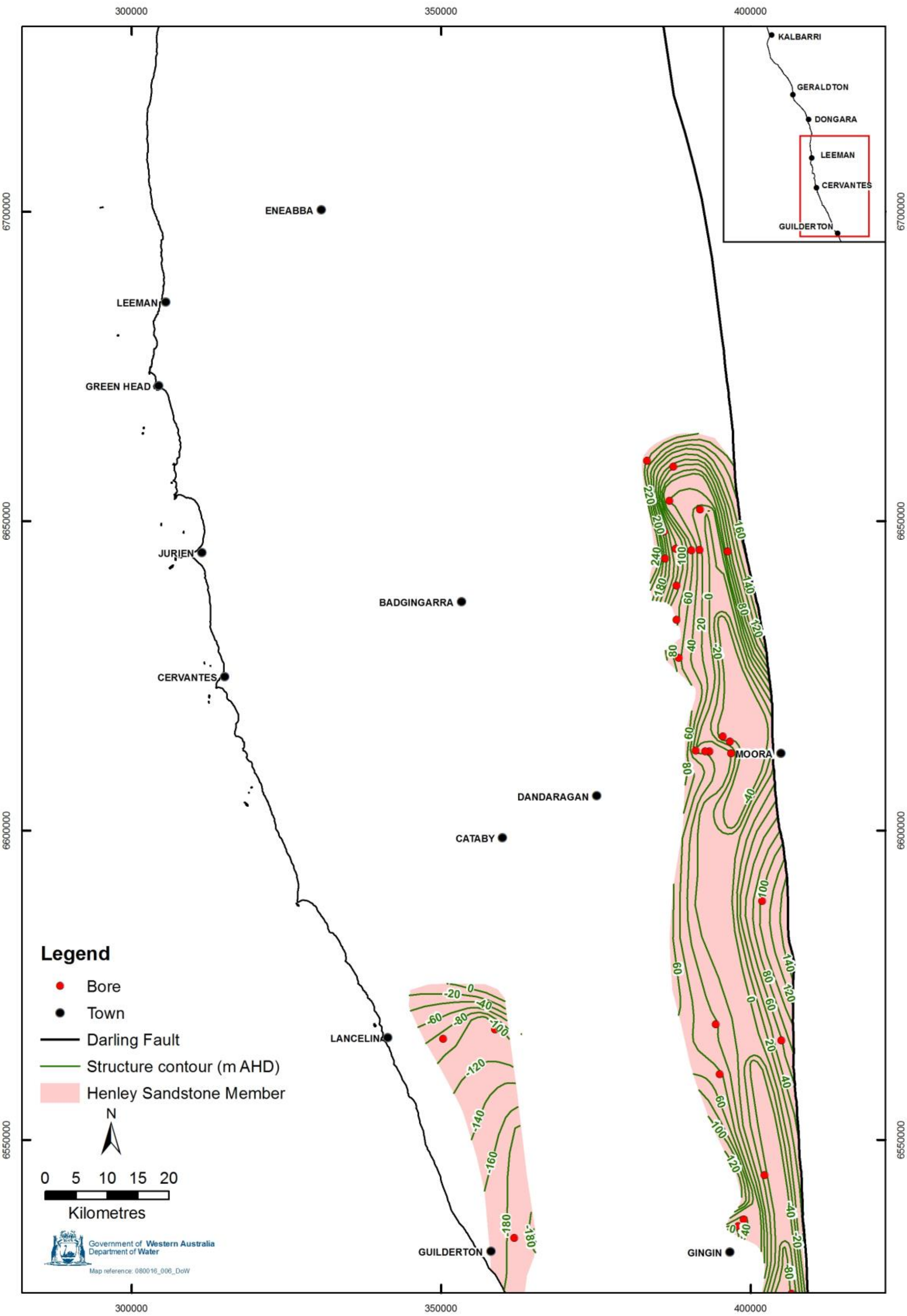


Figure 43 Henley Sandstone Member: contours on base of unit

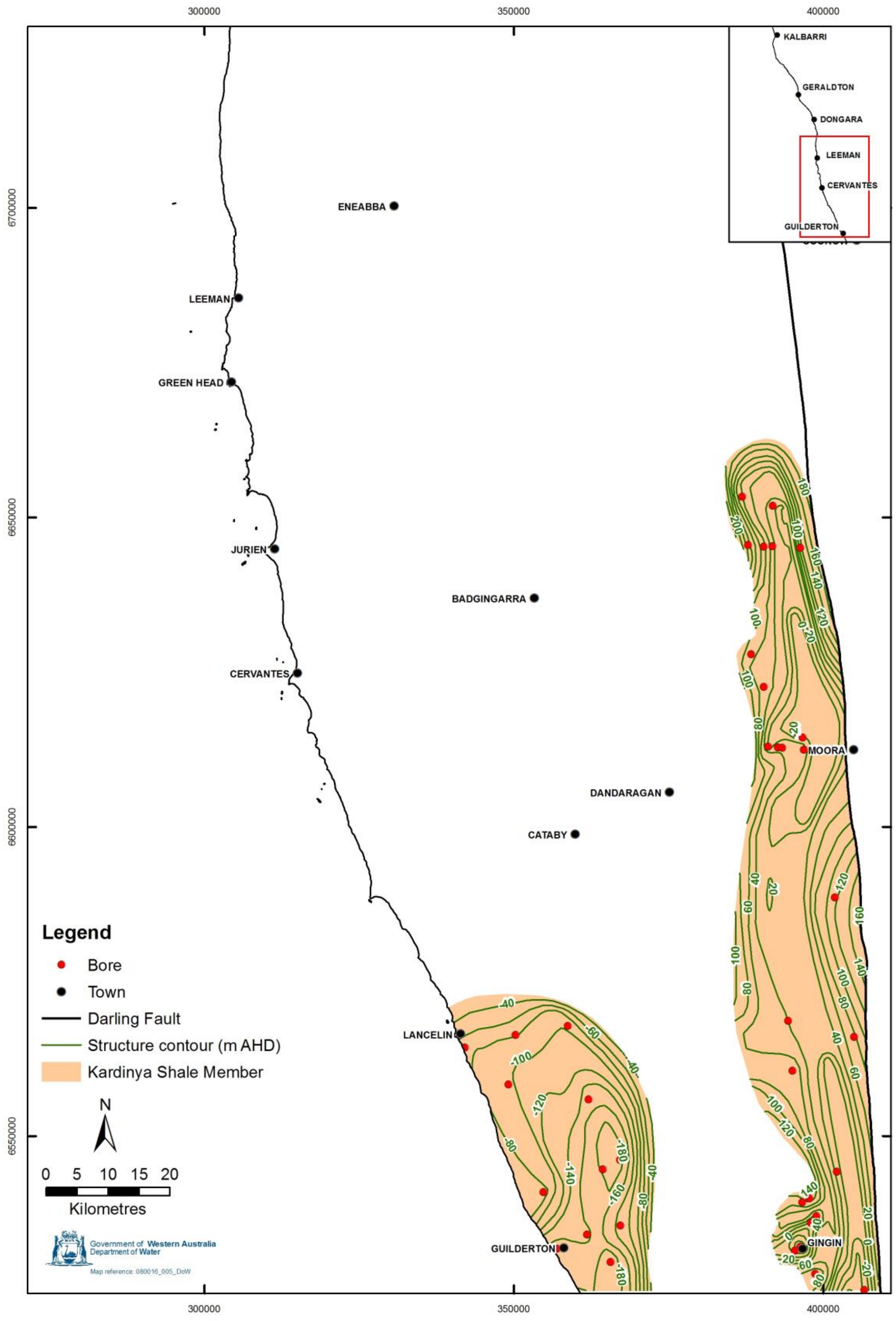


Figure 44 Kardinya Shale Member: contours on base of unit

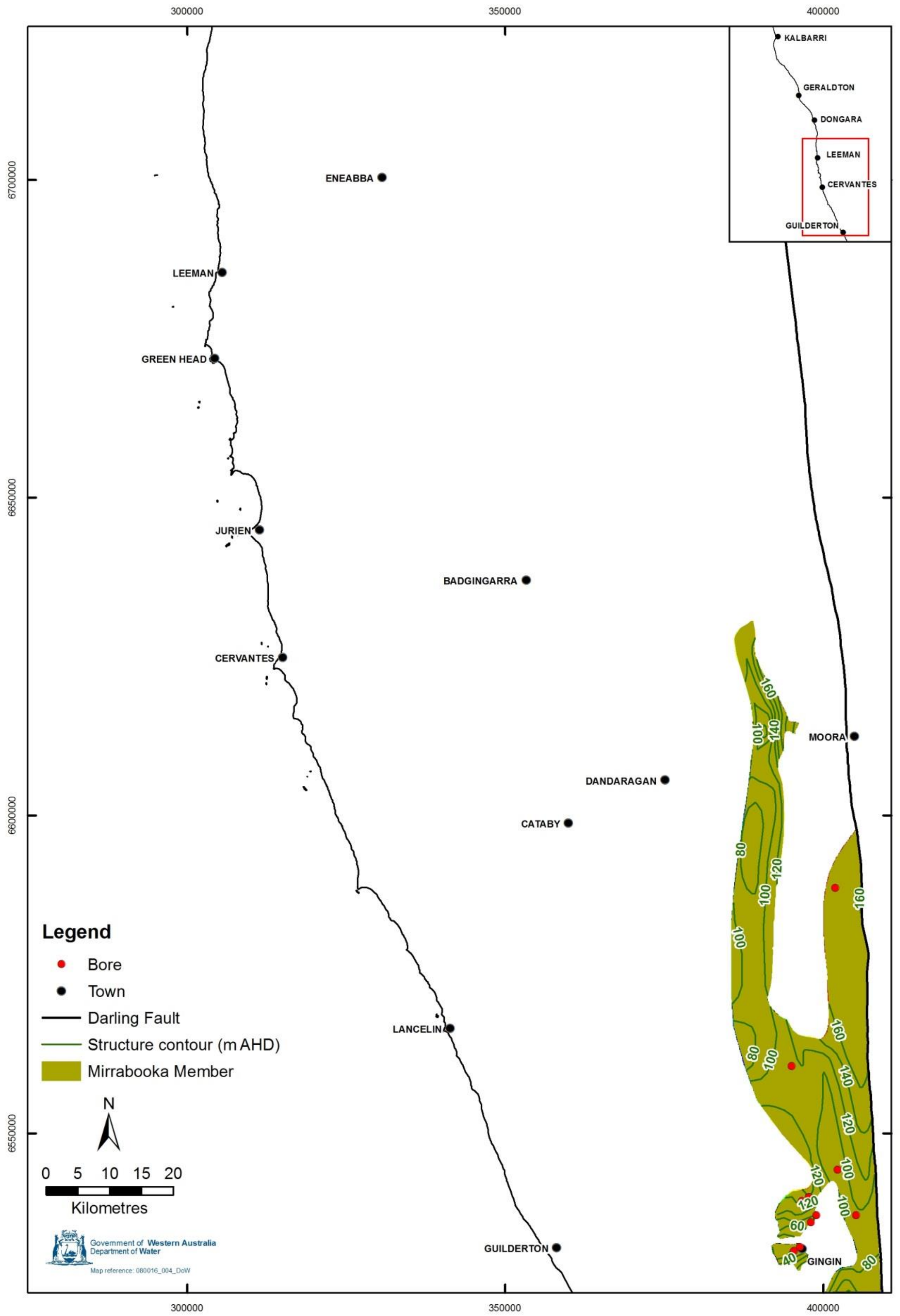


Figure 45 Mirrabooka Member: contours on base of unit

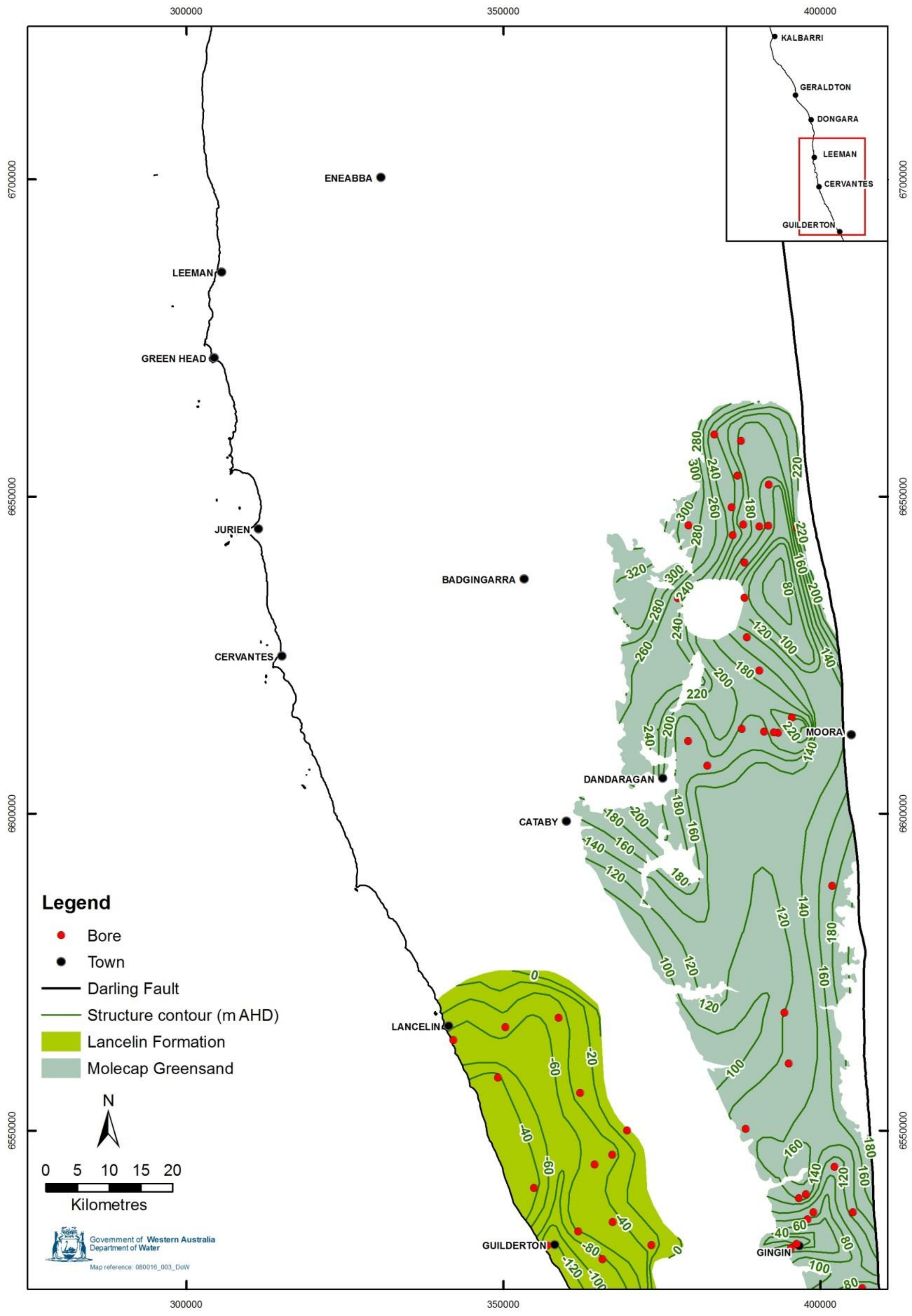


Figure 46 *Molecap Greensand (including Gingin Chalk and Poison Hill Greensand) and Lancelin Formation: contours on base of unit*

4.21 Surficial deposits

Pre-Cenozoic deposits are variably overlain by surficial deposits associated with numerous palaeochannels and a likely impact crater basin at Yallalie (Figure 47). Sediments of the surficial deposits include valley-fill, colluvial, alluvial, lacustrine, swamp and eolian deposits, and weathered lateritic profiles. Surficial deposits are considered separately to the superficial formations associated with the Swan Coastal Plain.

Table 10　　Surficial stratigraphy

Period	Epoch	Stratigraphy	Max. onshore thickness (m)	Lithology	Depositional environment
Quaternary (2.6 Ma-present)	Holocene	Alluvium, colluvium, lacustrine, swamp and channel deposits	10	Sand, silt, clay, calcrete, salt	Slopes, waterways
	Pleistocene	Channel deposits	153	Sand, clay and silt	Fluvial to marine
Neogene (23–2.6 Ma)	Pliocene	Yallalie Basin	111	Claystone, siltstone and sand	Lacustrine
		Monger Palaeochannel	35	Sand, gravel and clay	Fluvial to lacustrine

Monger Palaeochannel (Yarra Yarra Lakes)

The Monger Palaeochannel is the most extensive palaeochannel deposit in the northern Perth Basin region. The palaeochannel enters the Perth Basin near Three Springs and extends below the Yarra Yarra Lakes, south along the Darling Fault to beyond Moora (Figure 47). The sediments of the palaeochannel underlie parts the Yarra Yarra Lakes and the Coonderoo River (Yesertener 1999a). It possibly follows the northern branch of the Moore River and may underlie the Wannamal Lakes system as far south as Barn Road, 15 km north-east of Gingin before joining the Brockman River east of the Darling Fault (Kay & Diamond 2001).

The Monger Palaeochannel is infilled with a basal fluvial sand and gravel variably overlain by plastic clay. The sands are fine to very coarse grained, poorly to moderately sorted, subangular to subrounded, and are coloured yellowish brown, reddish brown to greenish brown and grey. Grain size and gravel content increases with depth at some sites (Yesertener 1999b). It also contains occasional layers of clayey and silty fine-grained sand.

At the southern end of Yarra Yarra Lakes, the palaeochannel sand is overlain by pale yellowish brown clay with minor sand clay (Yesertener 1999a). This clay possibly extends northward within the channel, but is absent to the south of Yarra Yarra Lakes. Palynology from clay samples indicates a late Miocene – early Pliocene age (Milne 1999).

Calcrete up to 10 m thick is also present south of Yarra Yarra Lakes. Palaeochannel deposits 35 m thick were intersected in the Yarra Yarra Lakes investigation between Carnamah and Watheroo (Yesertener 1999a, b).

Deposits of the Monger Palaeochannel unconformably overlie the Proterozoic Moora Group; whereas south of Yarra Yarra Lakes, they overlie progressively younger Mesozoic formations including Triassic Kockatea Shale and Lesueur Sandstone, Jurassic Cattamarra Coal Measures, and the Cretaceous Parmelia and Coolyena groups. Beneath Wannamal Lakes, the palaeochannel overlies the Leederville Formation or Coolyena Group (Kay & Diamond 2001). Cenozoic sand and clay colluvium unconformably overlies the palaeochannel deposits, which can be difficult to distinguish from the palaeochannel sediments. (Yesertener 1999a).

Other channel and palaeochannel deposits

Surface water drainage lines on the Dandaragan Plateau are commonly flat-bottomed valleys with ephemeral wetlands that become infilled with sands. Some examples of this are the truncated headwaters of Eneabba Creek, and the headwaters of Minyulo and Caren Caren brooks to the south-east of Dandaragan (Commander 1981; Kay 1999). Other examples are provided below.

A significant thickness of channel infilling in modern valleys was first noted by Barnett (1970) in the Arrowsmith River valley where the Arrowsmith bores (3, 6 and 15) intersected interpreted channel deposits up to 65 m thick (Barnett 1970b). The deposits are silty, fine- to medium-grained sand with coarse-grained layers in upper parts; whereas the lower part contains mainly clay with some minor yellowish brown silt and sand, but is dark grey where unweathered. The palynology suggests a significant range in geological age. Pollen assemblages from the Arrowsmith bores are dominated by eucalyptus species indicating that the unit is non-marine and younger than Miocene, possibly Quaternary (Barnett 1970b). A dark clay outcrop between Arrowsmith bores 4 and 8 is a channel deposit remnant that has been dated as Pliocene to Pleistocene (Barnett 1970b). Subsequently, a thickness of 153 m was found in Eneabba Line bore EL6 in the valley of Eneabba Creek (Commander 1978), with a similar thickness in a nearby production bore. The channel deposits intersected in Eneabba Line bore EL6 comprise medium- to coarse-grained, well sorted sand with minor clay and accessory heavy minerals with nodular ferruginous sandstone developed at the watertable. The substantial thickness of sediments indicates that the valley was cut by a larger drainage system, with infilling occurring after capture of the headwaters of Eneabba Creek by the Hill River.

In the Capitela Palaeochannel, the sand deposits may be as much as 40 m thick (HydroConcept 2012). The channel deposits unconformably overlie older formations, mostly the Yarragadee Formation and the Parmelia Group, but also Permian formations in the east, and are typically overlain by Quaternary alluvium and colluvium. It is unknown if the channel deposits are contemporaneous with the Yallalie Basin deposits (described below), but some overlap in the time of deposition is likely.

In 2013 and 2014 DAFWA carried out exploratory drilling in the Gillingarra Palaeochannel between Gillingarra and New Norcia on the Yilgarn Craton, outside the northern Perth Basin (Figure 47). The investigation encountered up to 193 m of sediments (Speed & Kellin 2015). It is not clear how these sediments relate to palaeochannel sediments in the Perth Basin.

Yallalie Basin deposits (impact crater)

An interpreted impact crater at Yallalie, 30 km north-west of Moora, has created a sediment-filled basin about 12 km in diameter (Figure 47 and Figure 48). The impact structure coincides with a circular topographical depression and radial features evident from digital elevation mapping. Muthawandery Creek, a tributary of Minyulo Brook, drains the basin through the southern rim.

The sediments within the Yallalie Basin accumulated between 2.5 and 3.6 Ma (Dodson & Ramrath 2001) and contain a rich and diverse assemblage of Pliocene pollen types dominated by A*llocasuarina/Casuarina* and *Myrtaceae* (mostly eucalyptus), similar to modern south-western Australia flora communities (Itzstein-Davey 2003).

The deepest part of the Yallalie Basin is located near petroleum well Yallalie 1, where it is 177 m deep with a basal elevation of 38 m AHD. It gradually shallows to the east where it is 166 m deep (basal elevation of 57 m AHD) within the Agrifresh bore TB1, and 98 m (130 m AHD) at Agaton 3.

Balleau and Passmore (1972) first recognised the presence of post-Miocene sediments infilling a basin or valley based on the thick deposits and topography surrounding the 'Yallalie depression'. Playford et al. (1976) described the area as an anticlinal feature, and named it the Muthawandery Structure; however, there was a poor appreciation of its origin. Seismic profiles captured by Ampol in 1990 indicated chaotic reflections of intensely disturbed sediments to a depth of about 2 km, characteristic of an impact feature (Economo 1991). Subsequent drilling of petroleum exploration well Yallalie 1 confirmed a localised basin with Pliocene-aged sand, clay and silt to a depth of 177 m (Economo 1991). Despite no conclusive petrographical or geochemical evidence, the morphology, presence of an allochthonous breccia deposit, and seismic reflection data is consistent with a meteorite impact feature (Dentith et al. 1999).

Geological data for the Yallalie Basin is available from a number of holes drilled within the basin, including Agaton bores 2 and 3, irrigation bore Agrifresh TB1, a stratigraphic hole drilled in 1998 and exploratory petroleum wells Cypress Hill 1 and Yallalie 1 and 2 (Dodson & Ramrath 2001).

The sedimentary sequence within the Yallalie Basin comprises a basal claystone and siltstone overlain by a sandstone unit that is concealed beneath Quaternary sand. The lower sequence of laminated silt and claystone with algal and carbonate-rich layers are black and olive grey, with traces of pyrite (Dodson & Ramrath 2001). Petroleum well Yallalie 1 intersected 111 m of this silt/claystone unit (66–177 m). The presence of dinoflagellate and algal tissue in clay and silt suggests deposition in a swamp to lacustrine setting (Dentith et al. 1999).

The overlying sandstone sequence is interbedded with carbonaceous clay and silt. It is about 54 m thick in petroleum well Yallalie 1 and is a similar thickness in other bores penetrating the unit (Economo 1991). It has a base elevation of about 150–160 m AHD. In petroleum well Yallalie 1, the overlying sandstone sequence is mottled light grey to pale yellow-brown, predominantly medium to coarse grained, moderate to well sorted, subangular to subround sand with traces of pyrite, thin carbonaceous beds and limonite (Economo 1991).

The Yallalie Basin deposits unconformably overlie the Cretaceous sediments of the Leederville Formation, which are light grey or cream at the unconformity contact (Dentith et al. 1999). There is extensive disruption of older sedimentary formations underlying the basin to a depth of about 2 km, and a central area 3–4 km across where the formations have been uplifted by about 700 m (Dentith et.al. 1999). Quaternary surface sands up to 15 m thick cover the older basin deposits.

Laterite

The surface of the Mesozoic formations has been extensively lateritised across the northern Perth Basin east of the Gingin Scarp and on basement rocks. Typically, the weathering profile consists of 2–3 m of leached quartz sand overlying massive ferruginous laterite up to 5 m thick of vesicular or concretionary rocks composed of iron and aluminium oxides (Mory 1994a). Beneath the laterite is a profile of weathered parent material up to 40 m thick that often includes a mottled zone over a pallid zone composed of significant kaolin clay. Sand at the top of the profile has been removed from substantial areas and redeposited as colluvium and alluvium within valleys, or as eolian sand, leaving laterite exposed on hilltops.

Lateritic sandstone and conglomeratic silicified deposits with minor siltstone, described as the Pindilya Formation, occur east of the Northampton Inlier, and extend into the Carnarvon Basin (Flint et al. 2000).

The laterite formed during periods of high rainfall, possibly 900 mm/yr, as a soil horizon within a zone of watertable fluctuation (Playford et al. 1976), although it is unlikely that the high gradients in the slope of the laterite surface could be maintained as a watertable in very permeable strata. It developed upon a plateau surface similar to the present day with slopes of up to 10° along surface water drainage lines (Playford et al. 1976). Originally thought to have developed during the Pliocene to Pleistocene (Prider 1966; Playford et al. 1976), palaeomagnetic data (Schmidt & Embleton 1976) suggest that the laterite formed earlier, during the Late Oligocene to Early Miocene (Johnstone et al. 1973).

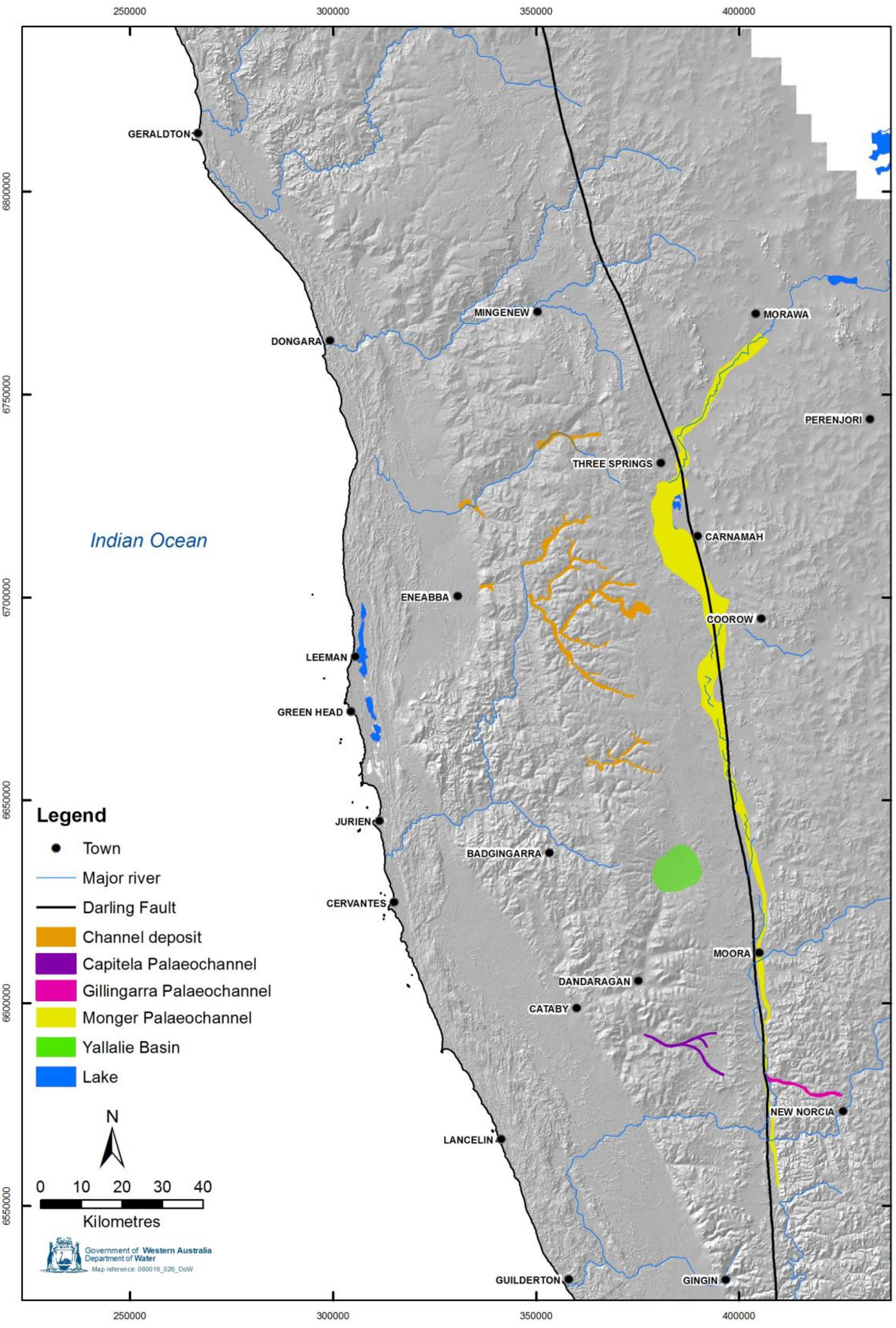


Figure 47 Surficial deposits: extent

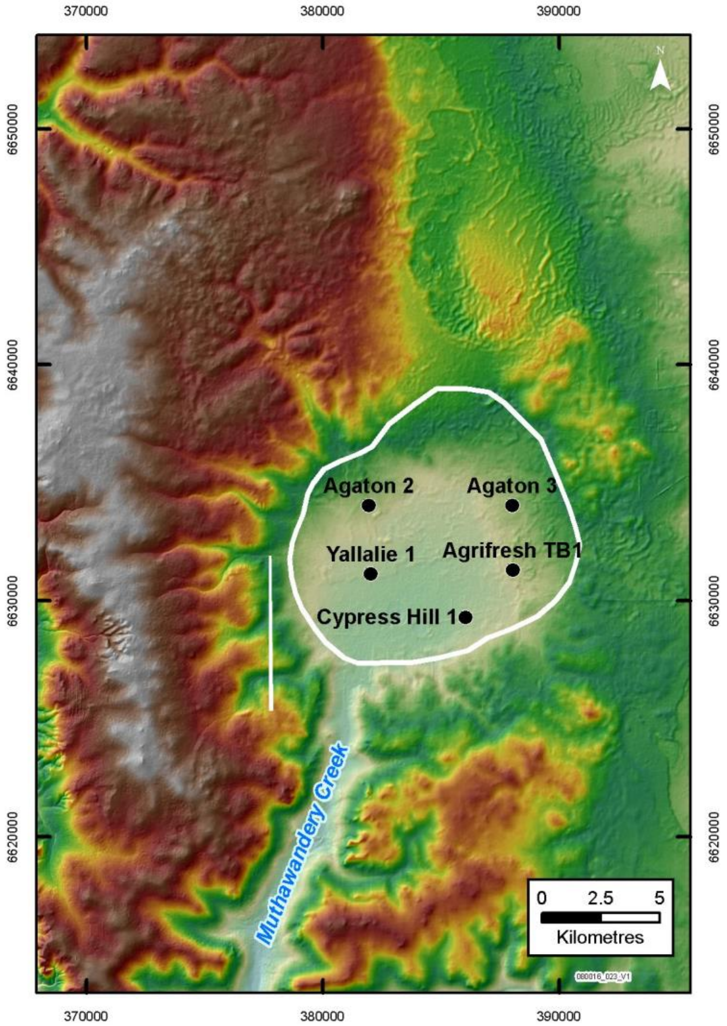


Figure 48 Digital elevation mapping showing Yallalie Basin

4.22 Superficial formations

The term 'superficial formations' was introduced by Allen (1976) to refer to the Quaternary sediments on the Swan Coastal Plain. The term has since been expanded to incorporate Pliocene sediments, including the Ascot and Yoganup formations (Moncrieff 1989; Moncrieff & Tuckson 1989) and is widely used as an informal group name (Briese 1979; Davidson 1995; Kern & Koomberi 2013, Tuffs 2011). In depositional order, they comprise the Ascot and Yoganup formations, Guildford Formation, Muchea Limestone, Bassendean Sand, Tamala Limestone, Becher Sand and Safety Bay Sand (Table 6 and Figure 49).

The superficial formations consist mainly of interbedded sand and clay, with limestone near the coast (Tamala Limestone) and at the base in some areas (Ascot Formation). They unconformably overlie a gentle, westward sloping erosional surface on Mesozoic sediments and have a maximum thickness of about 150 m and a typical thickness between 30 and 50 m (Figure 50). The geological cross-sections in Figure 51 show the stratigraphic relationships of superficial formations with underlying pre-Cenozoic lithologies.

Ascot Formation

The Ascot Formation is a calcareous marine deposit from the Pliocene age (Playford et al. 1976). The sediments were originally named the Ascot Beds (Playford et al. 1976), but were later renamed the Ascot Formation by Cockbain and Hocking (1989). The Ascot Formation is extensive between Guilderton and Cervantes, forming a north-trending belt beneath the central part of the coastal plain parallel to the Gingin Scarp (Moncrieff & Tuckson 1989; Kern 1988).

The Ascot Formation consists of hard to friable, light grey to fawn calcarenite with thinly bedded, coarse- to medium-grained sands. The calcarenite can be cavernous in the south. The sands are poorly sorted and angular to rounded and include shell fragments consisting of a rich molluscan fauna with abundant spicules and foraminifera (Kern 1988; Moncrieff & Tuckson 1989). Phosphate nodules and phosphatised fossils are at the base of the formation at some locations (Kern 1988).

The Ascot Formation was deposited in a shallow-water open-marine environment with minimal terrigenous contribution (Kern 1988), possibly a carbonate facies along a marine barrier sandbank, including a landward sand facies (Yoganup Formation) (Baxter & Hamilton 1981).

The Ascot Formation is typically 10–20 m thick, with a maximum thickness of 31.5 m in Salvado S13A near Seabird (Figure 52). The formation thins northward and is absent south of the Nambung River.

The Ascot Formation disconformably overlies the Yarragadee Formation in the north, Leederville Formation in the south, and Lancelin Formation near Lancelin. It is unconformably overlain by the Guildford Formation or Bassendean Sand and may interfinger with the Yoganup Formation to the west (Baxter & Hamilton 1981; Kern 1993a).

Yoganup Formation

The Yoganup Formation is a sand-dominated deposit representing a relic shoreline from the Pliocene age (Mory 1994a). The type section is in an open-cut mine near Yoganup (MGA Zone 50, 370433 m E, 6276070 m N), 200 km south of Perth (Low 1971).

The Yoganup Formation is a paralic deposit consisting of a prograding coastal sequence of dune, beach and deltaic deposits (Baxter 1982). The formation is dominated by fine- to coarse-grained, subangular to subrounded quartz sand, with minor clay and discontinuous concentrations of heavy minerals (Kern 1988). South of Lancelin, the sands are light grey to green-brown (Moncrieff & Tuckson 1989) and north of Cervantes, the sands are orange-brown to yellow (Nidagal 1995; Kern 1997). The sands are often leached and ferruginised, and are frequently associated with lenticular beds of kaolinised feldspar. A coarse-grained basal unit with gravels and pebbles is also common (Nidagal 1995). Heavy minerals (e.g. ilmenite, zircon and rutile) deposited along previous shorelines can be abundant and are mined at Eneabba and Cooljarloo, north of Cataby.

The Yoganup Formation is generally less than 10 m thick, but can be up to 21 m thick north of Gingin. The Yoganup Formation is a thin, discontinuous layer of fine-to-coarse sand along the eastern limit of the Swan Coastal Plain at the base of the Gingin Scarp (Baxter 1977, 1982). It has also been identified as a discontinuous deposit south of Eneabba in a belt up to 9 km wide and between Cervantes and Dongara (Kern 1993a, 1997; Nidagal 1995).

The Yoganup Formation unconformably overlies the Leederville Formation, Yarragadee Formation and Lesueur Sandstone. It may interfinger with the Ascot Formation to the west (Baxter & Hamilton 1981; Kern 1993a), although Moncrieff and Tuckson (1989) found that it overlies the Ascot Formation in the Salvado project area (Gingin Brook to Moore River). The Yoganup Formation is unconformably overlain by the Guildford Formation or Bassendean Sand, and near the Gingin Scarp is overlain by recent alluvium or colluvium. In the south near Lancelin, the western portions of the Yoganup Formation are overlain by the Tamala Limestone.

Guildford Formation

The Guildford Formation is a predominantly fluvial, clay-rich deposit adjacent to the Gingin Scarp. The sediments of the Guildford Formation were originally named as the 'Guildford Clays' by Aurousseau and Budge (1921). The terminology was later revised to 'Guildford Formation', which included a clayey and sandy facies (Low 1971). The name of Guildford Clay was later reinstated to refer to the clayey sediments, while the sand portion was attributed to the Gnangara Sand (Davidson 1995). In 2007 Gozzard reevaluated the Guildford Formation and described its relationship with the Gnangara Sand (Gozzard 2007).

The Guildford Formation comprises clay and sandy clay with lenticular beds of very fine to coarse sand. It is multicoloured, ranging from black and grey, to brown, yellow and mauve. The unit is mostly of fluvial origin, with estuarine and shallow marine intercalations, and was deposited at the coalescence of alluvial fans deposited by rivers draining the Gingin Scarp. The Guildford Formation is Pleistocene in age, based on fauna from the marine horizons in the Perth area (Darragh & Kendrick 1971).

The unit is present throughout the eastern part of the coastal plain at the base of the Gingin Scarp and is typically 30–40 m thick. The Guildford Formation interfingers with the Bassendean Sand to the west (Moncrieff & Tuckson 1989; Kern 1988; Nidagal 1995) and lies unconformably over Mesozoic lithologies or over the Yoganup Formation or Ascot Formation, where present (Moncrieff & Tuckson 1989; Kern 1997). The Guildford Formation is predominantly exposed at the surface, except where overlain by Tamala Limestone to the west or by colluvium near the Gingin Scarp (Nidagal 1995; Kern 1997).

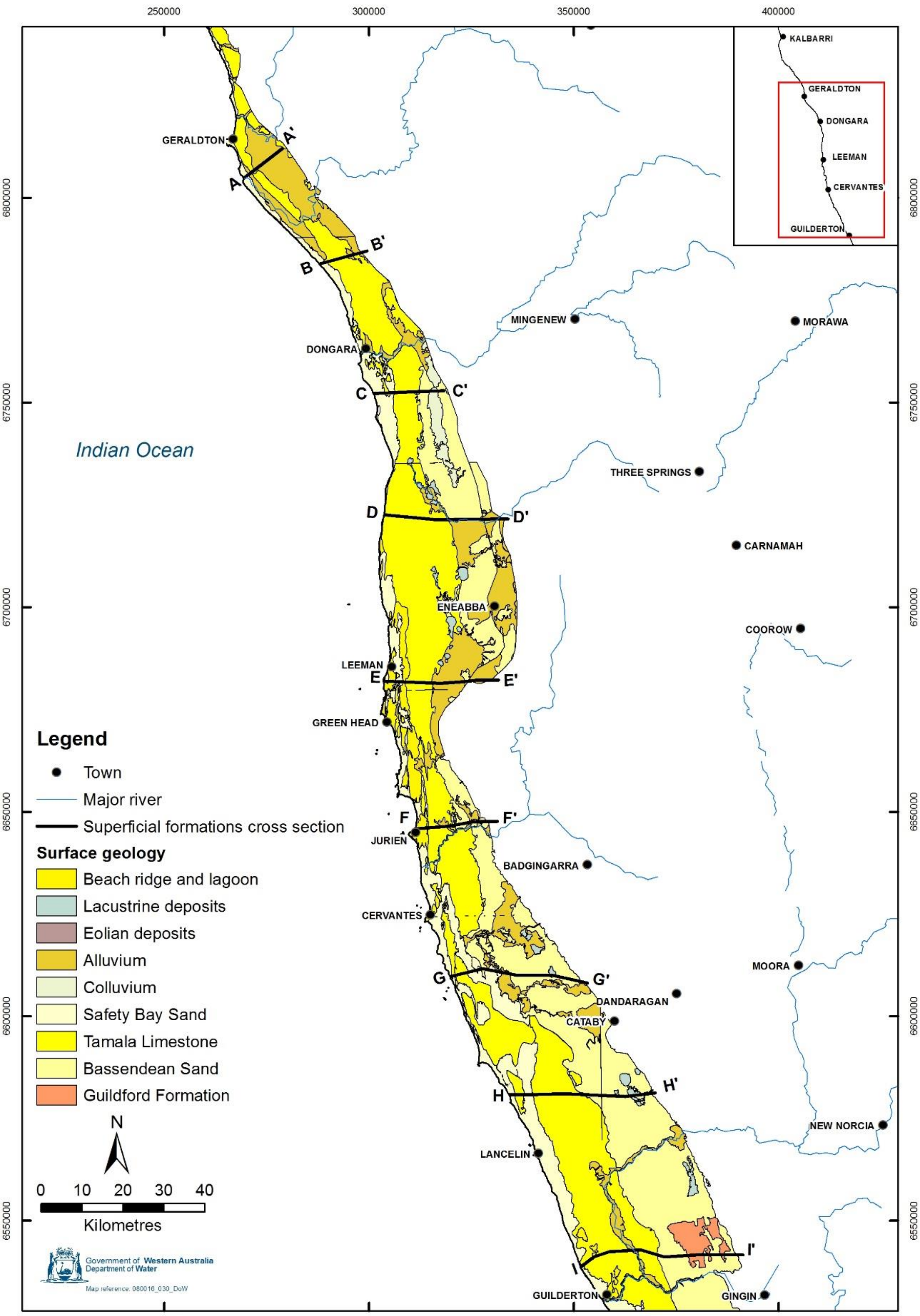


Figure 49 Superficial formations: surface geology with geological cross-sections

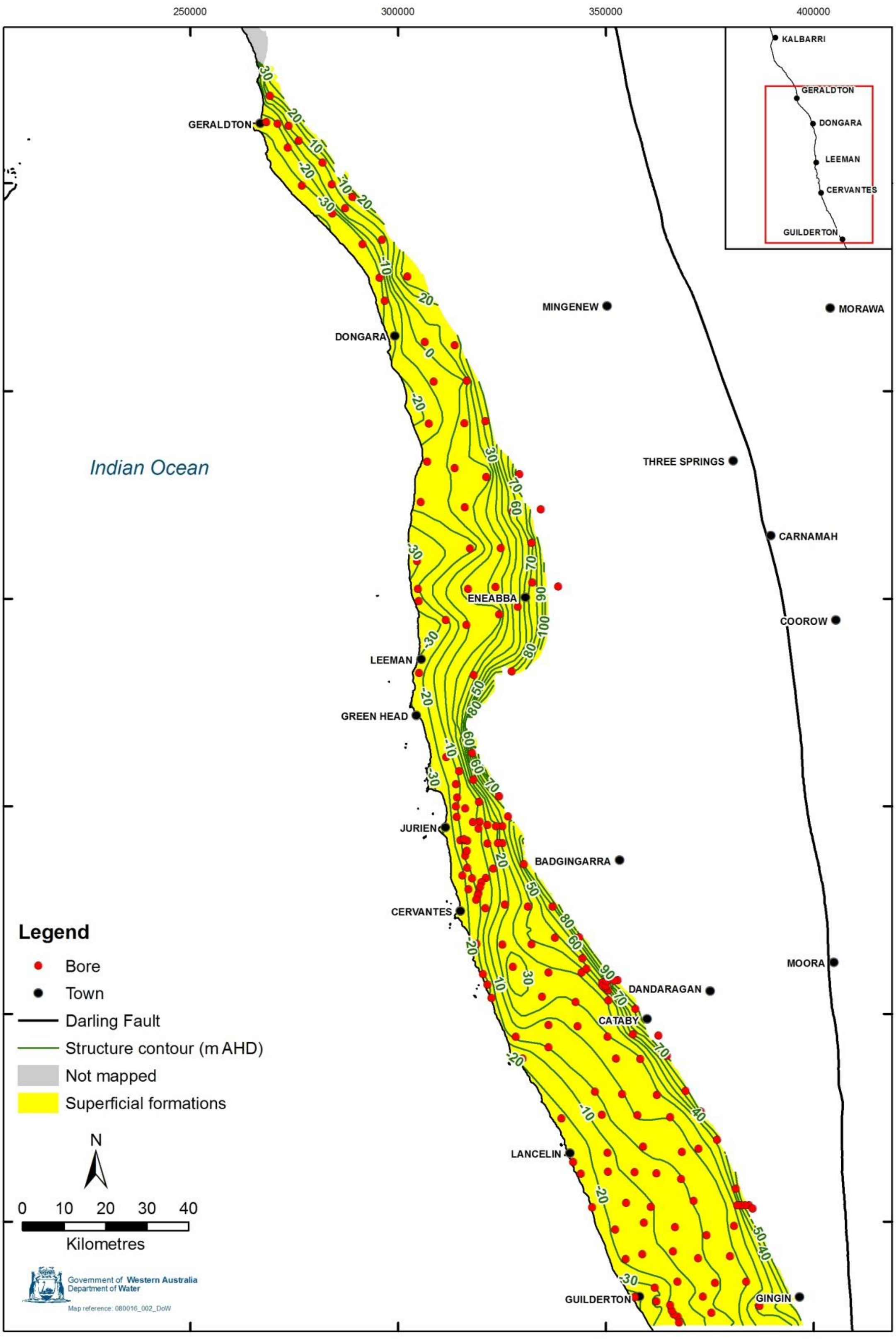


Figure 50 Superficial formations: contours on base of unit

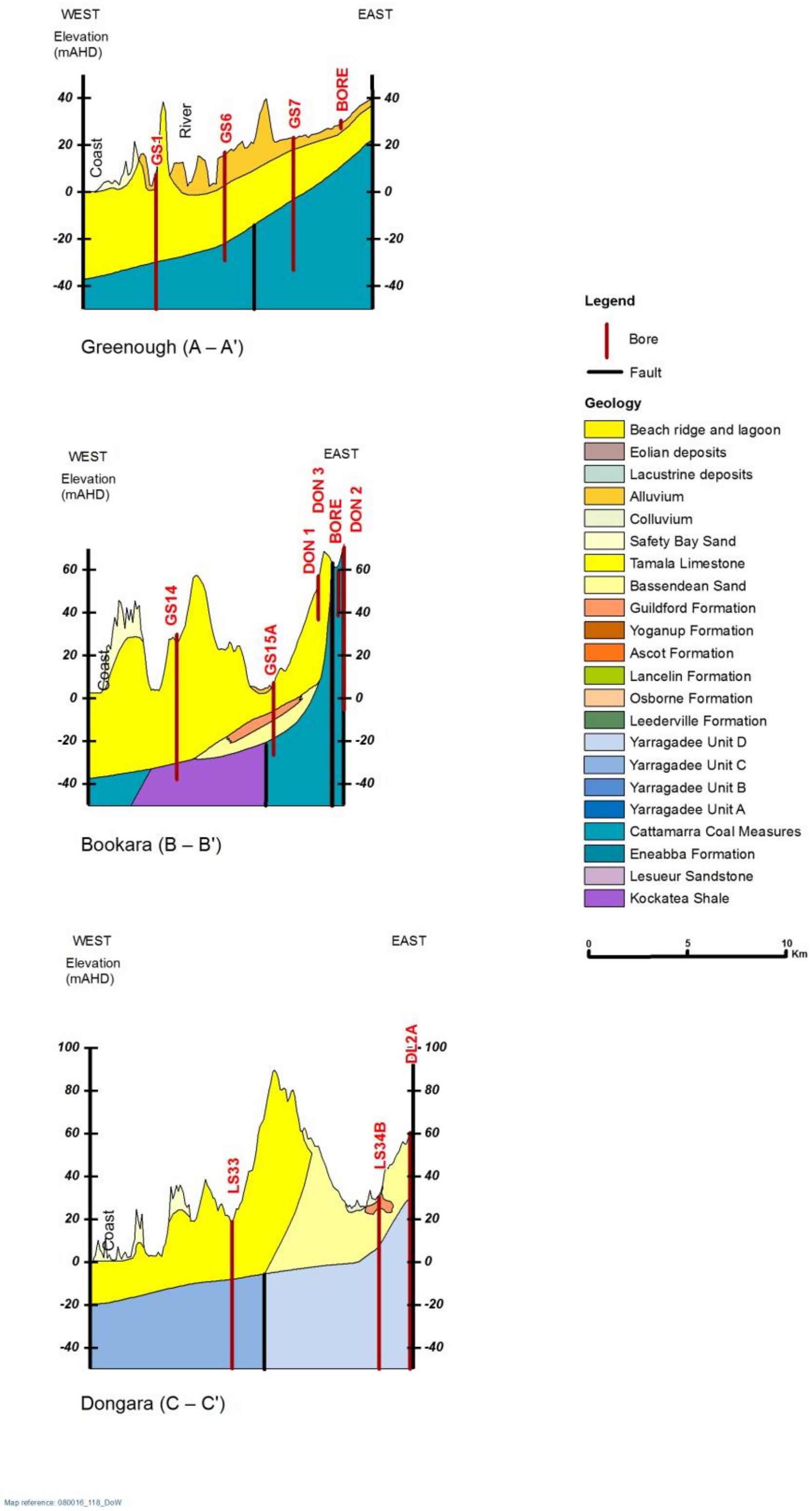


Figure 51 Geological cross-sections showing stratigraphical relationships of superficial formations

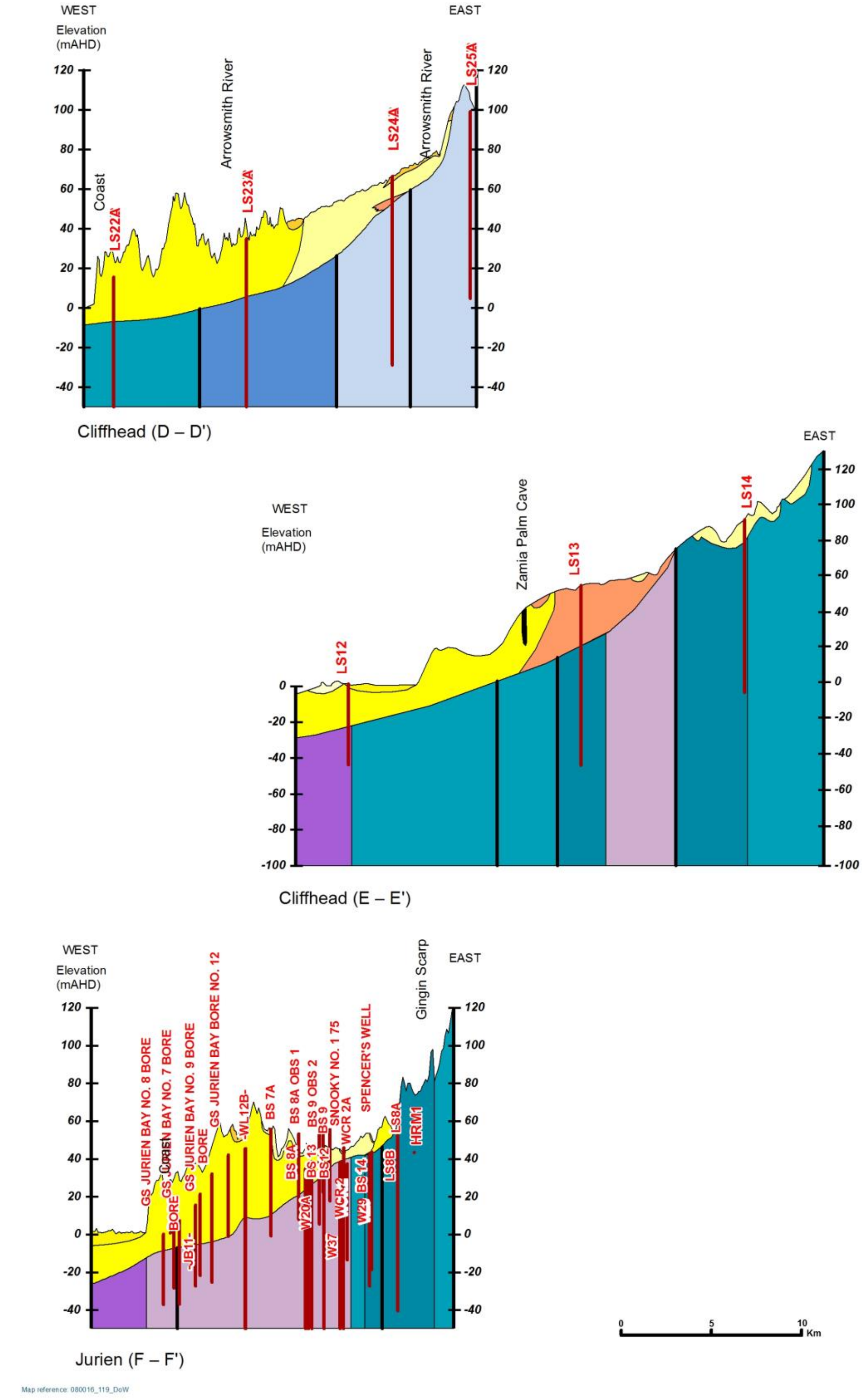
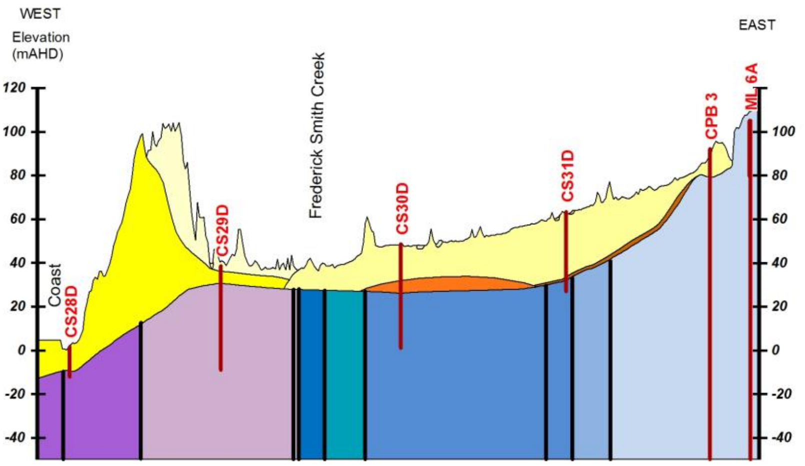
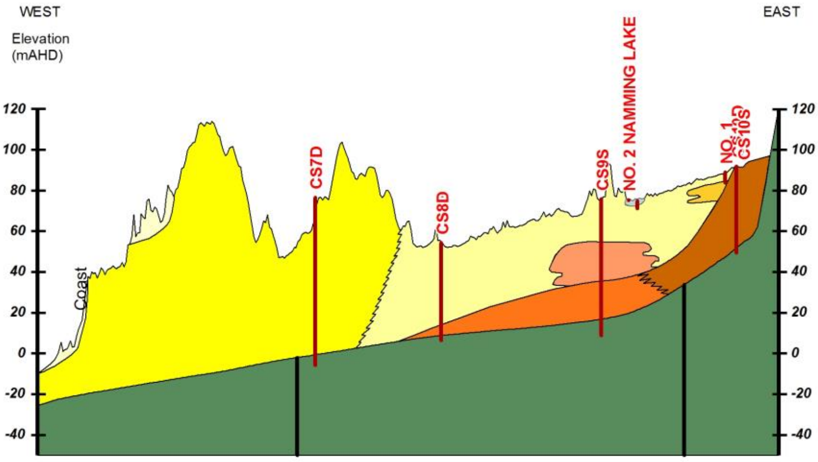


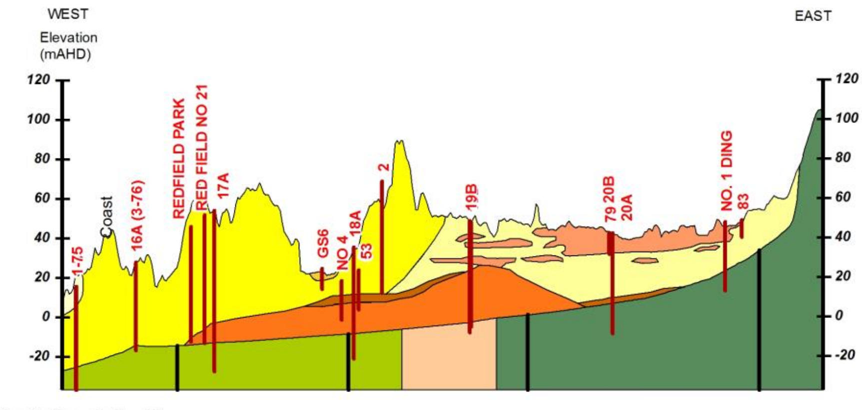
Figure 51 Geological cross-sections showing stratigraphical relationships of superficial formations (continued)



Cervantes (G – G')



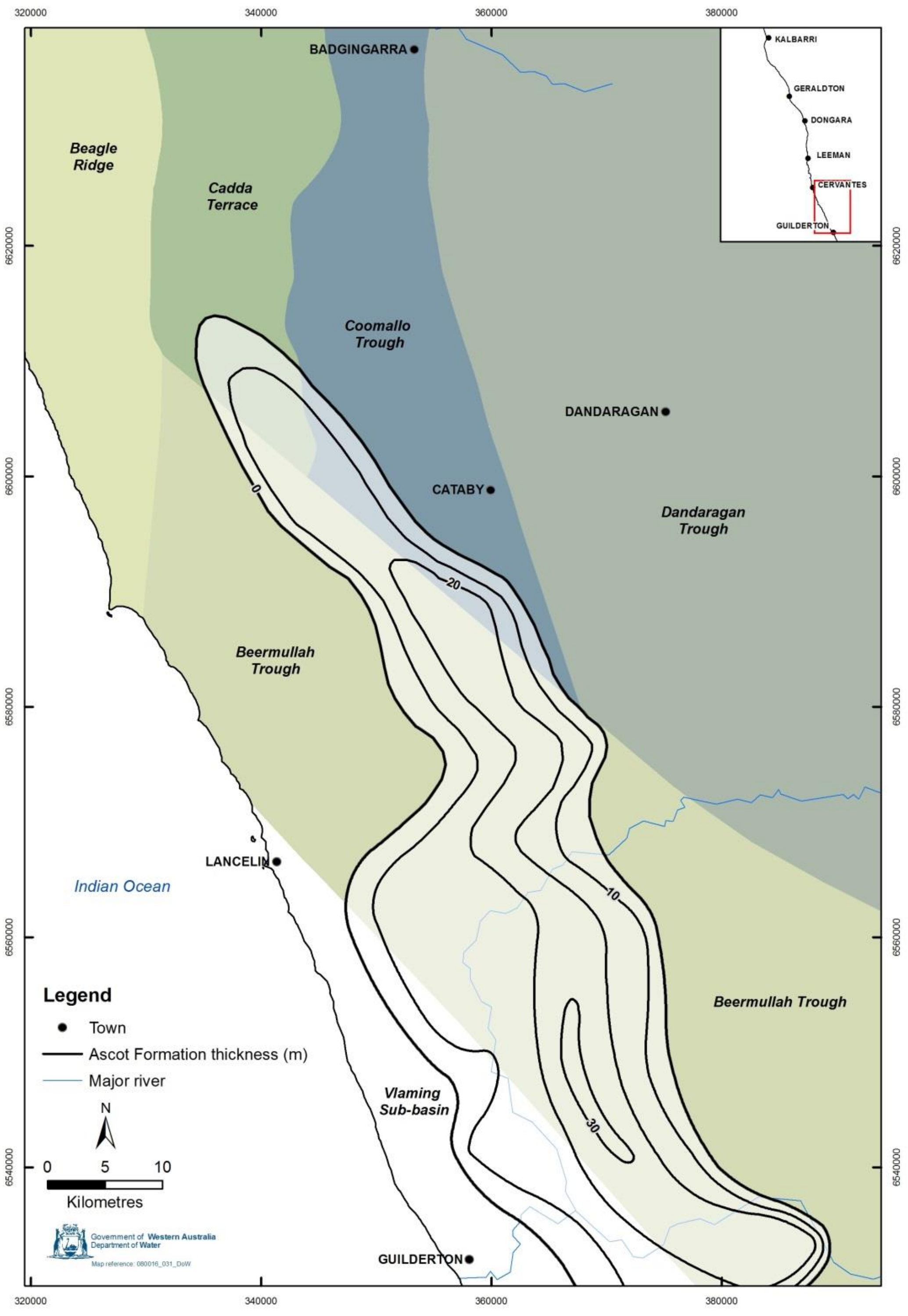
Lancelin (H – H')



Gingin Brook (I – I')

Map reference: 080016_120_DoW

Figure 51 Geological cross-sections showing stratigraphical relationships of superficial formations (continued)



(after Moncrieff & Tuckson 1989, Kern 1993a)

Figure 52 Ascot Formation: isopachs

Muchea Limestone

The Muchea Limestone is a thin shallow limestone deposit on the central and eastern Swan Coastal Plain. The unit was first recognised by Glauert (1911) and formalised by Fairbridge (1953), who named it after the town of Muchea about 40 km north-east of Perth.

The Muchea Limestone is a sandy and marly limestone (Playford et al. 1976), cream to yellow-brown, fine to medium grained, thinly bedded, and generally soft and friable, but can be hard. Some of the limestone is iron-stained to give a distinctive red colour (Hocking et al. 1976; Archer et al. 1977). The limestone contains algal laminations in places (Archer et al. 1977) and is locally fossiliferous (Moncrieff & Tuckson 1989).

The presence of freshwater gastropods suggests a lacustrine depositional environment (Kendrick 1978) during the Late Pleistocene or early Holocene (Moncrieff & Tuckson 1989). Some of the deposit may have formed by precipitation of carbonates in poorly drained pools (Archer et al. 1977).

The limestone is present in low-lying areas along Gingin Brook, near Big Bootine Swamp, and on the west bank of the Moore River (Hocking et al. 1976; Archer et al. 1977). It has not been observed to the north of Moore River. Generally, the limestone is discontinuous and less than 2 m thick, although shells in drill cuttings suggest it may reach over 11 m thick (Moncrieff & Tuckson 1989). The Muchea Limestone is either exposed at the surface or unconformably overlain by a thin cover of reworked Bassendean Sand.

Bassendean Sand

The Bassendean Sand is a widespread sand deposit from the Pleistocene epoch that covers the central Swan Coastal Plain (Playford et al. 1976). The Bassendean Sand was originally defined as a fluvial, dune, shoreline and shallow marine deposit (Playford & Low 1972). The definition of the Bassendean Sand was later restricted to the eolian sand dune deposits and the underlying fluvial and shallow marine sediments were defined as a sand facies of the Guildford Formation (Deeney 1989; Moncrieff & Tuckson 1989; Kern 1993, 1997; Nidagal 1995; Gozzard 2007). Davidson (1995) later redefined the Bassendean Sand and Guildford Formation in the Perth metropolitan area.

The Bassendean Sand consists of a light grey, grey-brown to brown, fine to medium- and coarse-grained, moderate to well sorted subangular to subrounded quartz sand. Upward-fining sequences or bimodal grain-size distribution with fine grained and coarse to very coarse grained quartz are common (Davidson 1995; Kern 1997). Traces of feldspar and carbonates are present, as well as high concentrations of heavy minerals along relic shorelines. North of Cervantes, the sands are poorly sorted (Kern 1997). North of Leeman, basal conglomerates are common, which may be calcareous in places (Nidagal 1995; Kern & Koomberi 2013). Near the watertable, the sands are frequently ferruginous and weakly cemented by limonite precipitate, which is colloquially referred to as ‘coffee rock’.

Deposition of the Bassendean Sand alternated from shallow marine to fluvial environments during one or more periods of relatively stable sea level higher than current levels (Davidson 1995). It includes shoreline, dune and fluvial settings. Estuarine and shallow marine intercalations are present at the base, while dune deposits dominate the upper portion (Kern 1993).

At the surface, the Bassendean Sand forms discontinuous low sand hills throughout the central Swan Coastal Plain, known as the Bassendean Dune System (McArthur & Bettenay 1960). The thickness of the sand is variable and largely dependent on the surface topography. The Bassendean Sand is thickest in the south, with a maximum of up to 53 m near Cataby (Kern 1988), and thins to the north where it is typically 10–30 m thick. The Bassendean Sand is not identified north of Dongara (Kern & Koomberi 2013).

The Bassendean Sand unconformably overlies Mesozoic lithologies, or where present, the Yoganup or Ascot formations (Moncrieff & Tuckson 1989; Kern 1997). It interfingers with the Guildford Formation in the east and is overlain by colluvium along its eastern extent near the Gingin Scarp (Nidagal 1995; Kern 1997). To the west, it is overlain by Tamala Limestone (Kern 1988; Davidson 1995).

Tamala Limestone

The Tamala Limestone is a calcarenite sand deposit along the coastline of both the Perth and Carnarvon basins. The Tamala Limestone was named by Playford et al. (1975) to describe calcareous sediments previously referred to as 'Coastal Limestone' or 'Tamala Eolianite' (Logan 1968) that extend along the coastal fringe of the Perth and Carnarvon basins. The type section is an outcrop at Womerangee Hill on the Zuytdorp Cliffs about 100 km north of Kalbarri in the Carnarvon Basin (Playford et al. 1975).

The Tamala Limestone consists mostly of calcarenite sand, with variable amounts of quartz sand and minor clayey sediments. It is cream, yellow-brown and light grey in colour, fine to coarse grain size and moderately to very well sorted. An orange limonite coating on the sand is common. It is composed of quartz sand and skeletal fragments, mostly of foraminifera and molluscs, together with traces of feldspar and glauconite, as well as phosphate-rich nodules near the base where it overlies Cretaceous lithologies in the south (Moncrieff & Tuckson 1989). The limestone is characterised by large-scale eolian cross-bedding and contains common relic soil horizons and calcified root structures (Playford et al. 1976; Kern 1997). Clayey lacustrine sediments are present between limestone ridges in some localities such as east of Wedge Island (Kern 1988) and near Geraldton. A basal clayey sand and clay is frequently present (Baddock & Lach 2003).

The calcarenite is variably cemented to form a lithified to friable limestone. The degree of cementation is greatest near the coast (Moncrieff & Tuckson 1989), and a hard 'capstone' is frequently developed at the top of limestone (Kern 1997). Leaching of carbonate by rainfall has left a residual yellow to white quartz sand as a surface cover, predominantly in eastern parts where it can be up to 100 m thick (Kern 1988).

In places, the loose sand has been eroded by wind action but pinnacles of calcified limestone are preserved. This effect can be observed at the Pinnacle Desert near Cervantes. Karstic features associated with dissolution of the carbonate in the limestone have developed over much of the Tamala Limestone outcrop. These karstic features include extensive development of vertical solution channels and cavities and solution pipes that may have developed from calcified root structures (Playford et al. 1976; McNamara 1983). These solution pipes and cavities are most common near the watertable and are often filled with sand. Cave systems are present at several locations including Nambung National Park, Drovers Cave National Park and nature reserves east of Leeman and Coolimba.

The Tamala Limestone developed as coastal dunes associated with successive sea-level stands (Playford et al. 1976), mostly from eolian deposits, but lower portions contain marine, littoral or lagoonal facies (Moncrieff & Tuckson 1989). Deposition commenced during the Middle Pleistocene and extended to the Late Pleistocene (Kendrick et al. 1991). The age of shell and coral material are between 117 100 and 132 000 years before present (BP) (Mory 1995b). The most easterly dunes form the Spearwood Dune System that consists of slightly calcareous eolian sand that remains after leaching of the underlying limestone (McArthur & Bettenay 1960).

The Tamala Limestone is present along the west coast as a band of successive ridges about 10–20 km in width parallel to the coast (Figure 49). North of Geraldton, on the margins of the Northampton Inlier, the formation narrows to less than 5 km. The thickness of the Tamala Limestone varies significantly, dependent on surface topography with an average thickness of about 40–50 m. The limestone probably reaches 120 m at Vern Hill (12 km north-east of Cervantes) (Kern 1997), and may be up to 150 m thick south of Nambung National Park (Kern 1988) and in the Hutt River area (Playford et al. 1976). There are frequent outcrops over the Spearwood Dunes and upon wave-cut platforms (<2 m AHD) exposed in the Coolimba–Cervantes and Denison areas. Coastal cliff outcrops are also common and are up to 75 m high (south of Hutt River). The base of the formation slopes westward, extending to about 25 m below sea level along the present coastline (Commander 1981).

The Tamala Limestone unconformably overlies various subcropping pre-Cenozoic formations. Near its eastern margin on the Swan Coastal Plain, the formation overlies and possibly interfingers the Guildford Formation and Bassendean Sand (Kern 1993; Kern & Koomberi 2013). North of the coastal plain, the Tamala Limestone unconformably overlies an eroded surface upon Proterozoic basement, and Triassic and Jurassic sediments. The Tamala Limestone is disconformably overlain by the Becher Sand (where present) and Safety Bay Sand adjacent to the coast. Sandy alluvium overlies the formation along the Moore River and Gingin Brook (Moncrieff & Tuckson 1989), and west of the Gingin Scarp sand from outwash fans north of Dongara (Kern & Koomberi 2013).

Becher Sand

The Becher Sand consists of near-shore marine deposits from the Holocene that continue to be deposited along the coast on the Swan Coastal Plain (Semeniuk & Searle 1985). Previously, these marine sands were included with the Safety Bay Sands, but were separated owing to different depositional environments and apparent age (Semeniuk & Searle 1985; Mory 1994a). The type section for the Becher Sand is an outcrop adjacent to the coast at Woodman Point, about 20 km south of Perth.

The Becher Sand is light grey to light grey-brown, fine to medium grained, well sorted, subrounded to rounded quartz and skeletal sand (Semeniuk & Searle 1985). It includes a fawn coloured, calcareous mudstone intersected over 2 m at Seabird in bore Seabird 1/75 (Moncrieff & Tuckson 1989).

The Becher Sand is present along most of the coastline of the Swan Coastal Plain and as low ridges parallel to the shore south of Leeman, at Jurien Bay and near Cervantes (Mory 1994a). The sediments of the Becher Sand are associated with littoral sandbanks, beach–dune ridges and a sea-grass bank sequence (Moncrieff & Tuckson 1989; Mory 1994a, 1995a).

The Becher Sand has been intersected by drilling at several sites between Guilderton and Lancelin, where it is generally only a few metres thick (Moncrieff & Tuckson 1989). In the Perth region, it is 10–15 m thick with a maximum of 20 m in the Rockingham area. The Becher Sand unconformably overlies the Tamala Limestone, and is often conformably overlain by the Safety Bay Sand (Moncrieff & Tuckson 1989).

Safety Bay Sand

The Safety Bay Sand encompasses the eolian sand dunes of the Holocene that continue to be deposited along the coast of the Swan Coastal Plain. The Safety Bay Sand was originally defined to include both eolian sand and shallow marine sand deposits (Passmore 1967; Playford & Low 1972) but the marine and shoreline components (Becher Sand) were later removed from the formation (Semeniuk & Searle 1985). The designated type section is from surface to 24 m depth in Rockingham bore R3 (MGA Zone 50, 378216 m E, 6427776 m N) in the Perth metropolitan area (Passmore 1967).

The Safety Bay Sand consists of cream to buff, loose to moderately cemented, fine- to medium-grain size calcareous sand. It is moderately to well sorted, and angular to rounded (Playford et al. 1976). The calcium carbonate content is generally greater than 50 per cent. The sand also includes fragments of molluscs, bryozoan and foraminifera as well as traces of heavy minerals (Kern 1997). This Holocene unit continues to be deposited (Playford et al. 1976).

The Safety Bay Sand occurs discontinuously along the entire length of the Swan Coastal Plain and extends up to 14 km inland (Kern 1988; Mory 1995a) forming dunes of the Quindalup Dune System (McArthur & Bettenay 1960). Most of the dunes are stabilised by vegetation cover, but there are significant areas of bare mobile dunes with parabolic dunes and blowouts developed north of Lancelin (Moncrieff & Tuckson 1989).

The thickness of the Safety Bay Sand is highly variable, and may exceed 100 m over parts of the coastal plain. The base of the sand is about 5 m below sea level at the coast (Kern 1988). The Safety Bay Sand unconformably overlies the Tamala Limestone, and near Cervantes overlies shoreline beach ridges of the Becher Sand (Mory 1995a).

Miscellaneous deposits

Minor Holocene deposits, usually less than 10 m in thickness, are found locally throughout the region (Lowry 1974).

Eolian deposits form isolated low sand ridges that are most extensive across the Victoria Plateau and Yarra Yarra region. The orange-coloured quartz sands have been derived mainly from sand at the top of the lateritic weathering profile. A wide dune containing gypsum sand has developed about the south-eastern margin of the Yarra Yarra Lakes (Baxter

& Lipple 1985). A similar dune sand deposit about 65 km north of Mingenew was found dated at between 15 000 and 120 000 years old (Mory 1995b).

Along the Gingin Scarp, clay to gravel and laterite clasts deposited in fans are derived from erosion of laterite-capped sediments in the Arrowsmith region and Dandaragan Plateau (Nidagal 1995; Kern 1997; Kern 1988, Kern & Koomberi 2013). Deposits of colluvium consisting mainly of sand washed down from the laterite above may also develop on slopes beneath laterite breakaways. Recent alluvium is common within the valleys of streams and rivers, including the Arrowsmith River (Nidagal 1995), the Moore River (Moncrieff & Tuckson 1989), Caren Caren, Minyulo and Mullering brooks (Kern 1988) and the Chapman, Greenough and Irwin rivers (Kern & Koomberi 2013). The alluvial deposits include silt and clay, often intercalated with fine- to coarse-grained subangular to subrounded quartz sand (Nidagal 1995; Kern 1988). The thickness of these alluvial deposits is generally less than 5 m, but can be up to 20–30 m in places (Kern 1997; Kern & Koomberi 2013).

Lacustrine and swamp deposits are found within interdunal wetlands and lakes throughout the coastal plain, particularly in the Bassendean Dunes (Kern 1988, Ryan 2012a). These sediments consist mainly of clay, peat and marl, but can also contain diatomite where there has been minimal clastic sediment input and thicknesses can vary (Mory 1994a; Kern 1988, 1997). At Lake Thetis, lakebed sediments are up to 8 m thick and underlie the Safety Bay Sand, reflecting the contraction of the lake basin (Ryan 2012a). Stromatolites are present at Lake Thetis, near Cervantes (Grey et al. 1990), and calcrete and halite salt deposits are present at the Yarra Yarra Lakes. A series of lagoonal and estuarine deposits underlying modern saltlakes are also found between Green Head, north of Jurien Bay and Coolimba, parallel to the coast. These lagoonal and estuarine deposits consist of marl, shell beds, clay, silt, gypsum and halite (Kern 1997), and at Hutt and Leeman lagoons are up to 5 m thick (Kern 1997).