Reinterpretation of the hydrogeology of the Leederville aquifer

Gnangara groundwater system

Looking after all our water needs

by

LA Leyland

Department of Water

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Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
National Relay Service 133 677
www.water.wa.gov.au

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For more information about this report, contact the Branch Manager, Water Resource Assessment.

Cover image: Snapshot of the salinity distribution of the Leederville aquifer in PETREL®.

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Summary

This report examines the three-dimensional geology and hydrogeology of the Leederville aquifer within the Gnangara groundwater system. The aquifer in this area is a vital water resource, and makes up ~20% of the Water Corporation Integrated Water Supply Scheme. The aquifer is hosted by complex, variable (heterogeneous) strata whose sedimentary characteristics, prior to this study, had not been investigated. In addition, a recent 1000 m deep bore (Q37) encountered strata that could not be explained by the current geological model. Earlier analysis of the Leederville groundwater salinity distribution showed no clear pattern or links with groundwater flow (Davidson 1995).

The report presents a detailed analysis of the heterogeneity, aquifer connectivity and salinity distribution of the Leederville aquifer, building on the broader analysis of Davidson (1995) and Davidson and Yu (2006). The existing dataset of archived downhole geophysical logs and groundwater data has been supplemented in this study by diamond drill core and geophysical logs from recent drilling, and also by newly compiled palynological reports and published groundwater ages. This extensive dataset had been integrated and interpreted using new 3D analysis software.

Analysis of drill core and downhole gamma ray logs reveal that the Leederville Formation was deposited in a tidally influenced, deltaic setting. This depositional setting explains the sediment distribution (or facies architecture) within the aquifer, and the size, distribution and connectivity of sand bodies which host groundwater flow. The facies architecture developed parallel to the Darling Fault, dividing the aquifer into north–south orientated zones with similar facies and hydrogeological properties. Maps describing this lateral variation in facies are presented for the first time in this report.

In particular, the Wanneroo Member, which constitutes the majority of the Leederville aquifer, is composed of delta plain deposits. Well connected, tidally influenced sand bodies are widespread throughout most of the study area, generating excellent aquifer connectivity. The overlying Pinjar Member is dominated by silt-rich, offshore facies that act as an aquitard due their poorly connected sand layers. In contrast, along the eastern margin of the study area, the Wanneroo Member is composed of poorly connected, fluvial sand bodies which generate moderate aquifer connectivity, and the overlying Pinjar Member is composed of sand-rich, shoreface facies that act as an aquifer due to their high sand percentage.

New isopach maps are presented for the Warnbro Group. There are some significant differences between the new maps and the isopach maps of Davidson (1995), especially in the east where this study has recognised considerable lateral variation in facies. In addition, the Pinjar aquitard facies are more eroded than previously thought. There is significant connection between the Wanneroo aquifer facies and the Superficial aquifer below the crest of the Gnangara Mound, including in the west where the Leederville aquifer discharges to the Superficial aquifer.

This study has found that the thickness and distribution of the Warnbro Group and the overlying Coolyena Group were influenced by contemporaneous fault activity.

The strata dip and thicken towards the downthrown side of the Badaminna, Serpentine and Darling faults, and the previously unrecognised Wanneroo Fault, indicating that fault activity occurred during deposition. This structural interpretation highlights the likelihood of increased connectivity between the Leederville and Yarragadee aquifers, and local hydraulic isolation of the Leederville aquifer. This is especially true in the north-western study area along the Badaminna Fault.

A comprehensive, 3D salinity distribution of the Leederville aquifer is presented for the first time. The salinity distribution correlates with the long-term flow patterns of the aquifer. The freshest water is found below the crest of the Gnangara Mound, highlighting the location and extent of the recharge zone. Two main flow paths have been recognised: a shallow, fresh young flow path associated with recent recharge, and a deeper, marginal to brackish, old flow path fed by regional flow. These flow paths highlight the two main sources of groundwater in the Leederville aquifer: local recharge superimposed on regional flow from the north. There is a contrasting salinity distribution and groundwater age to the west of the Badaminna Fault. This illustrates the hydraulic isolation of the offset portions of the Leederville aquifer and the hydraulic connection between the Leederville and Yarragadee aquifers, thereby highlighting the influence of the fault on groundwater flow.

It is anticipated that the conceptual geological and hydrogeological models presented in this report will provide a basis for calibration, assessment and future modification of the Perth regional aquifer modelling system. In addition, this report will be useful as a reference document in the interpretation and correlation of downhole geophysical logs and drill cores, as it provides both detailed descriptions of the Leederville aquifer and theoretical context. This report is a summary of PhD research by conducted by Leyland (2011), and the thesis can be consulted if further detail is required.

1 Introduction

1.1 Context

The Gnangara Mound is an area of elevated watertable in the central onshore Perth Basin, to the north of the city of Perth (Figure 1). The watertable mound, maintained by infiltration of rainfall, generates a downward hydraulic gradient from the Superficial to the underlying Leederville and Yarragadee aquifers. This vertical gradient promotes groundwater recharge of the deep aquifers, creating the Gnangara groundwater system, one of the most important water resources for the Perth metropolitan area. The Gnangara groundwater system supplies 60% of the Water Corporation Integrated Water Supply Scheme (IWSS). A third of this comes from the Leederville aquifer.

Rainfall on the Gnangara Mound has been declining since the 1970s, and global climate models predict that this drying trend will continue across south-western Western Australia (IPCC 2007). This decline in rainfall, combined with a growing population, has caused the Perth metropolitan area to become increasingly dependent on groundwater, which has contributed to a steady, long-term decline in watertable levels on the Gnangara Mound (Yesertener 2008). To help manage groundwater in the face of these challenges, the Department of Water has developed the Perth regional aquifer modelling system (PRAMS), a numerical groundwater flow model (Davidson and Yu 2006). The ability of this model to faithfully represent the groundwater system depends upon the accuracy of the underlying conceptual model. This conceptual model needs to be kept as up-to-date as possible, and the information in this report will help to do this.

1.2 Purpose and scope

The purpose of this project was to develop a 3D geological and hydrogeological model of the Leederville aquifer within the Gnangara groundwater system to advance understanding of natural groundwater flow. It is anticipated that the final conceptual flow model will be used to inform the future calibration of PRAMS.

The study took a geological approach to understanding groundwater flow by first investigating the depositional and structural history of the Leederville Formation by incorporating the principles of facies analysis and sequence stratigraphy. These characterisation techniques are used in the oil industry and have been identified as particularly useful for the characterisation of heterogeneous sedimentary aquifers (e.g.de Marsily et al. 2005, Galloway 2010). A better understanding of the heterogeneity of the Leederville Formation is necessary to create a realistic description of groundwater flow (e.g. Webb & Davis 1998, de Marsily et al. 2005). In addition, a recent 1000 m deep bore (Water Corporation bore Q37), (Martin 2007 pers. comm.) encountered strata that could not be explained by the current geological model, prompting reanalysis of the structural geology.

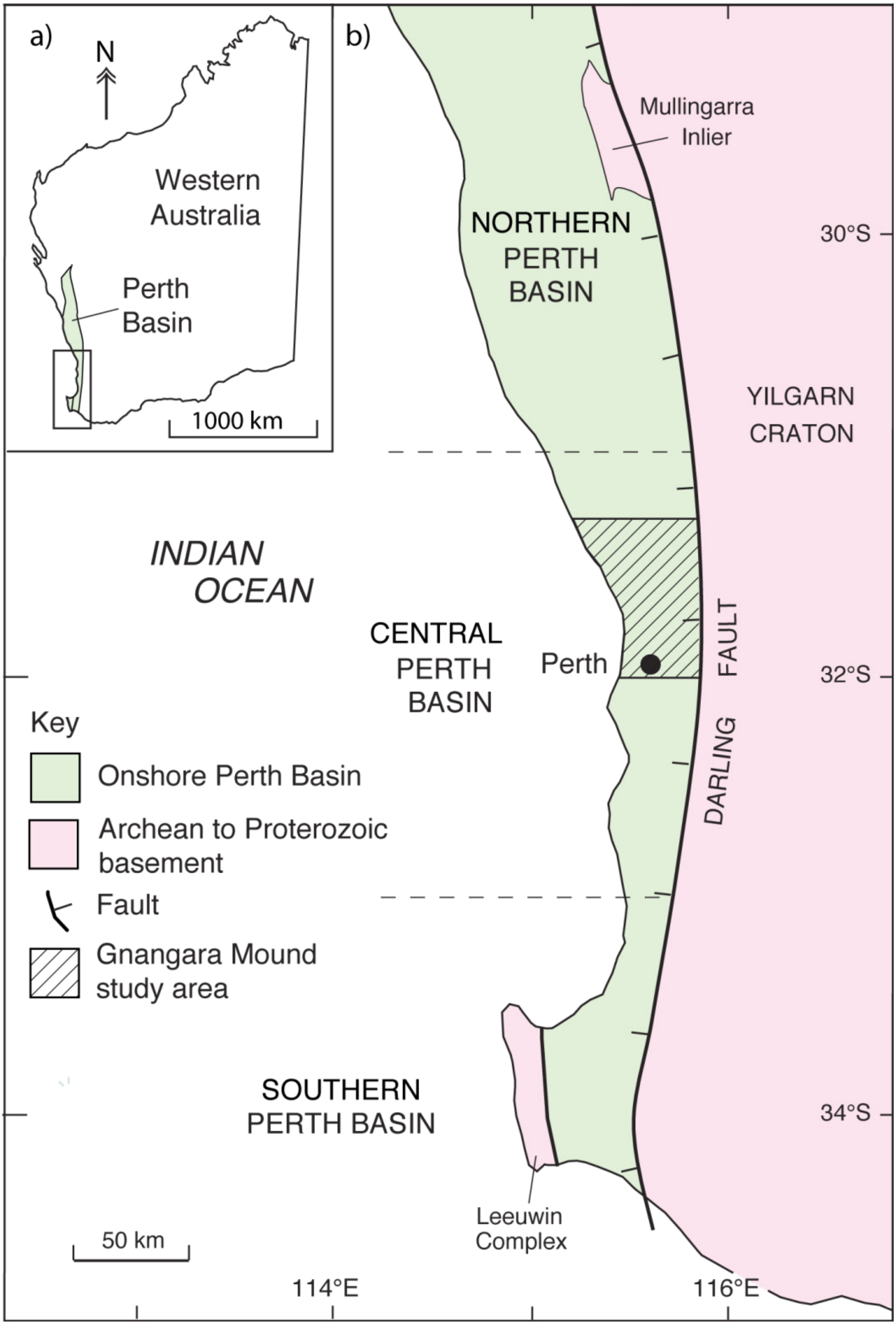


Figure 1 (a) Map showing the onshore Perth Basin. (b) Regional map showing the Gnangara groundwater system to the north of the city of Perth.

The hydrogeological analysis focused on the 3D groundwater salinity distribution of the Leederville aquifer. This distribution highlighted the recharge and groundwater flow patterns and was a useful complement to the hydraulic head distribution (e.g. Manzano et al. 2001). Earlier analysis of the salinity distribution by Davidson (1995) showed no clear pattern or links with groundwater flow.

Aims of the study

There were three aims.

Aim 1

Undertake detailed geological logging and facies analysis to establish the depositional setting of the Leederville Formation. The purpose of this is to help understand the heterogeneity of the Leederville Formation and to assist in the interpretation and correlation of downhole geophysical logs.

Aim 2

Correlate stratal surfaces, stratal packages and facies architecture in gamma ray logs, with reference to the depositional setting and biostratigraphic age data, to create a 3D geological model of Warnbro Group strata below the Gnangara Mound. The purpose of the model is to summarise the depositional and structural history of the Leederville Formation and the geological controls on the heterogeneity, thickness, fault offset and lateral continuity of the aquifer strata.

Aim 3

Establish the relationship between downhole resistivity and groundwater salinity for the Leederville aquifer, and create a 3D groundwater salinity distribution. Combine this salinity distribution with the geological model and distribution of hydraulic head and groundwater age to create a conceptual flow model for the aquifer.

1.3 Previous work

The onshore Perth Basin has been investigated through groundwater and petroleum exploration since the 1960s (reviews in Davidson 1995; Allen 1996; Crostella 1995; Crostella & Backhouse 2000; Davidson & Yu 2006). Groundwater exploration has focused on the onshore central and southern sections of the basin, while petroleum exploration focused on the northern and southern sections and the offshore central section.

Descriptions of groundwater resources have been developed by Cargeeg et al. (1987), Commander et al. (1991), Allen (1975), Allen (1976), Allen (1979), Allen (1981) and were consolidated by Davidson (1995). Davidson and Yu (2006) presented a revised hydrogeological model which is the basis for the current version of PRAMS. The improvement and calibration of PRAMS is ongoing, as the underlying geology and the aquifer parameters and recharge patterns are developed (e.g.

CyMod Systems 2009; Milligan 2009; Merrick 2009a, 2009b; Silberstein et al. 2009; Xu et al. 2009).

1.4 Data and methods

Sedimentology

This study used newly available diamond drill cores from two boreholes that intersected the Leederville Formation (Figure 2). They were Artesian Monitoring 26E (known as AM26E), drilled in 2007 by the Department of Water, and Beenyup 1/07 (known as BNYP 1/07), drilled in 2007 by the Water Corporation, (Water Corporation 2009). Three hundred metres of drill core through the Leederville Formation were logged in detail to collect sedimentological and trace fossil data. Logging was carried out at the Department of Mines and Petroleum core library in Carlisle. Facies analysis was undertaken to systematically describe and analyse the cores for paleoenvironmental reconstruction and to interpret the depositional setting. Representative sand samples were collected and petrographic analysis of thin sections was carried out using a Nikon polarising microscope. Point counting was undertaken to characterise modal composition and diagenetic features.

Palynology

At the two drill core sites, palynological analysis of 32 silt samples was undertaken by Dr John Backhouse (Backhouse Biostrat Pty Ltd). Strata at BNYP 1/07 were dated using marine microplankton, indicating deposition during Early to Late Hauterivian, whereas strata at AM26E could only be dated using terrestrial miospores, indicating a broader Hauterivian–Barremian age bracket. At sites without drill core, depositional ages were constrained using pre-existing biostratigraphic data from 82 palynological reports (Appendix C) (compiled by Backhouse 2005).

Petrophysics

This study used 158 downhole gamma ray logs and 124 downhole resistivity logs from deep (>100 m) bores drilled over the past 50 years (Figure 2, Appendix C). Downhole logs were analysed using Schlumberger PETREL® 3D analysis software at the Department of Water. Warnbro Group stratal packages with distinct gamma ray motifs were interpreted, based on the depositional setting of facies associations recognised in core, and their distribution was mapped. Stratal surfaces were identified and well logs were correlated using a sequence stratigraphic approach, focusing on correlating the surfaces that bound stratal packages. Fault trace and offset were identified where there was an abrupt change in the thickness of strata, and in depth and dip of stratal surfaces. A synthetic log of sand percentage was generated as outlined in the Dresser Atlas (1979), and sand percentage was mapped throughout the Warnbro Group using the kriging interpolation.

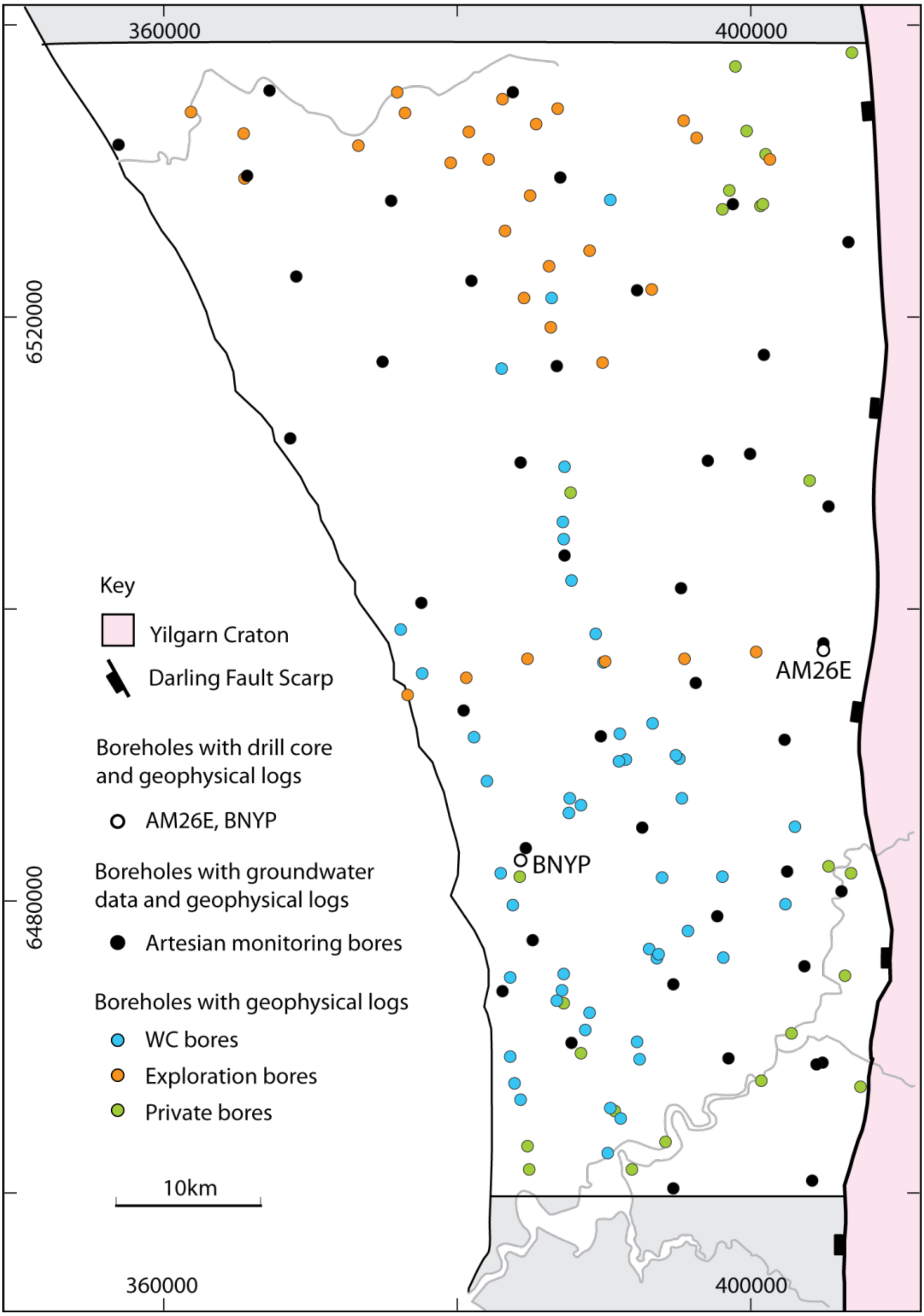


Figure 2 The Gnangara groundwater system, showing the distribution of borehole data used in this study, including the two labelled drill core locations AM26E and BNYP 1/07. Shaded areas lie outside the study area. Coordinate system: geocentric datum of Australia zone 50.

Hydrogeology

The formation resistivity factor for the Leederville aquifer was calculated using downhole resistivity logs and water sample conductivities from 30 groundwater monitoring bores. This formation factor measures the contribution of the sediment to the overall formation resistivity. Synthetic groundwater salinity logs were then calculated from 124 downhole resistivity logs. A salinity distribution for the Leederville aquifer was constructed using a 3D grid based on the proposed geology. Groundwater age data, hydraulic heads and head gradients were incorporated to investigate flow patterns and to create an overall conceptual flow model. Isopotentials were interpreted based on monthly hydraulic head data from September 1987, measured in 40 artesian monitoring bores and 170 Superficial aquifer monitoring bores.

1.5 Supporting research

This report is a brief summary of the results of PhD research by Leyland (2011). Those wishing to carry out further work in the Perth Basin should consult the thesis. Digital and paper versions are available at the libraries of the Department of Water and the University of Western Australia.

2 Depositional and structural history

2.1 Evolution of the Perth Basin

Crustal extension

The Perth Basin formed during the Late Paleozoic–Mesozoic break up of Gondwana, in the rift between Australia and Greater India (Royer & Coffin 1992). Rifting occurred from the Permian to Early Cretaceous along the north-western and western margins of Australia, culminating in continental separation in the Neocomian (Stagg et al. 1999). Multiple tectonic episodes, progressive separation of fault blocks and complex dip–slip fault reactivation have led to a number of interpretations of basin history (e.g. Iasky et al. 1991; Quaife et al. 1994; Mory & Iasky 1996; Song & Cawood 1999). Their interpretations highlight two main stress regimes. The Permian–Triassic regime, with extension orientated west-south-west to east-north-east, reactivated the existing north trending structural grain resulting from weaknesses in the underlying Precambrian basement (Byrne & Harris 1992; Harris et al. 1994; Dentith et al. 1994). The Jurassic to Early Cretaceous regime, orientated north-west to south-east, produced a transtensional setting with obliquity between the extension and the north–south structural grain. Consequently the basin is composed of a series of sub-basins, ridges, terraces and troughs (Figure 3).

Permian to earliest Cretaceous

Rifting created accommodation for deposition of Permian to earliest Cretaceous strata (Figure 4) in non-marine to locally shallow marine conditions (Crostella & Backhouse 2000). The north trending basin was connected to the Tethys Ocean in the north (Playford et al. 1976). During rifting, the depocentre of the basin shifted from south to north, with the Permian succession thickest in the southern Perth Basin, the Triassic succession thickest in the central Perth Basin, and the Jurassic succession thickest in the northern Perth Basin (Crostella & Backhouse 2000). Sediment provenance studies based on detrital zircons from strand lines on the Swan Coastal Plain (Sircombe & Freeman 1999) and from lower Paleozoic to Triassic strata (Cawood & Nemchin 2000) have indicated that southerly source regions such as the Proterozoic Albany Fraser Orogen and the Leeuwin Complex of the Pinjarra Orogen dominated sediment supply to the Perth Basin. This indicates that there was significant uplift of Proterozoic orogens and little input from the Archean Yilgarn Craton. However, recent provenance analysis of major and trace elements of minerals in the Leederville Formation suggests that local granitoids from the Yilgarn Craton were the principal source of sediment supply during the Early Cretaceous (Descourvieres et al. 2011).

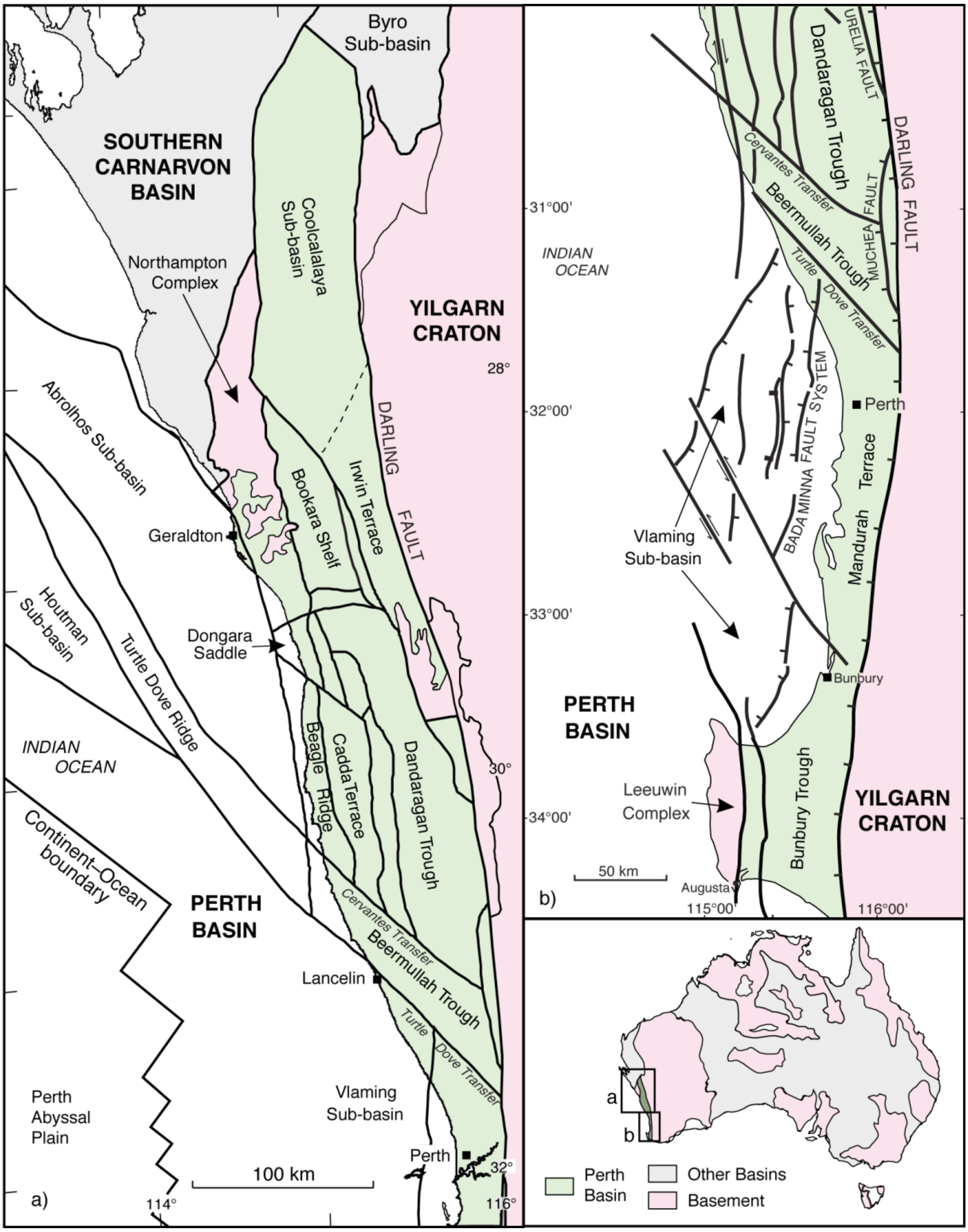


Figure 3 Geological maps showing location of Perth Basin and major tectonic elements and structures, including the Badaminna and Darling fault systems. (a) The northern and central Perth Basin (modified after Mory et al. 2005). (b) The central and southern Perth Basin (modified after Crostella & Backhouse 2000).

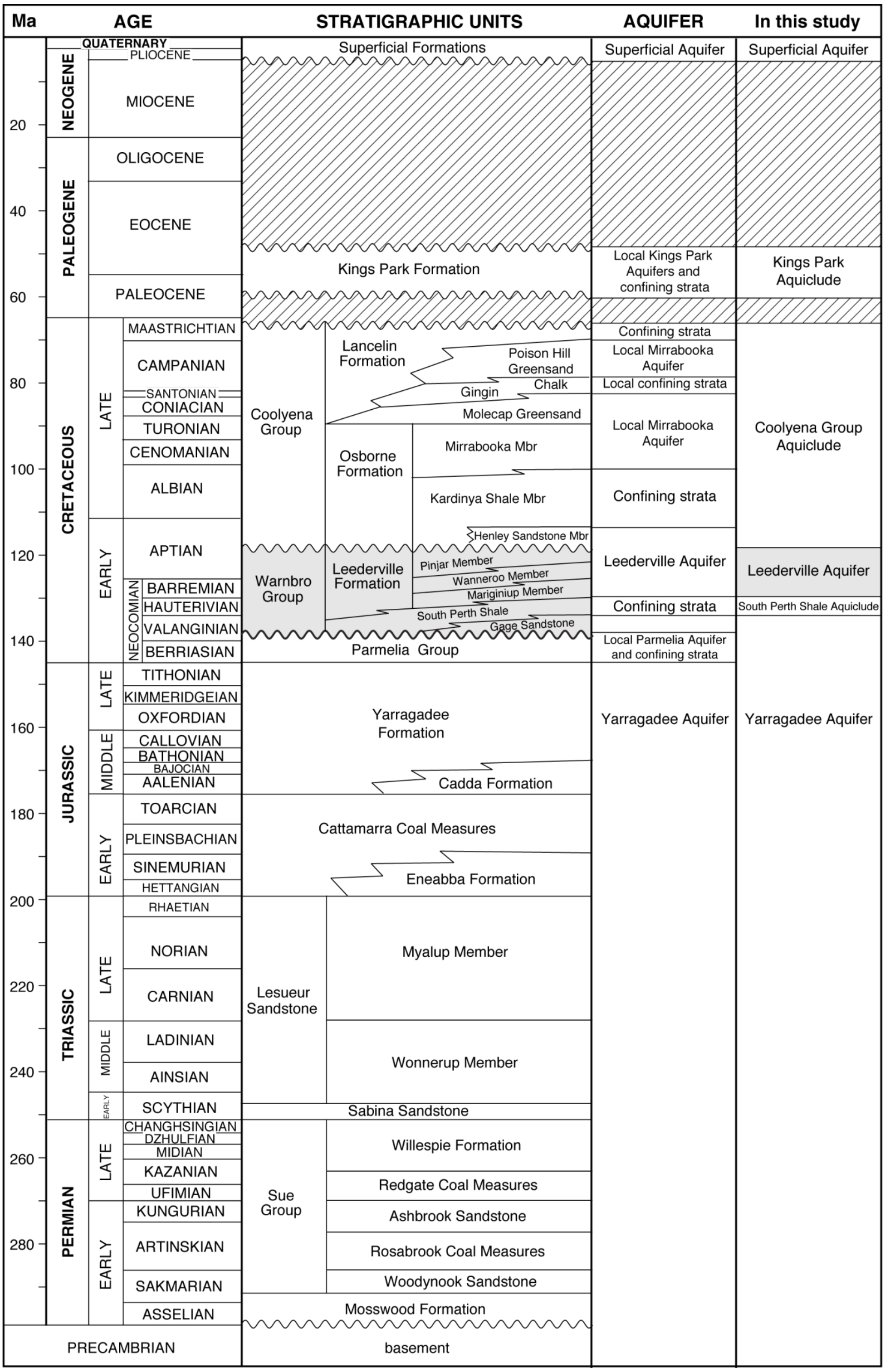


Figure 4 Lithostratigraphy and aquifers of the onshore central Perth Basin after Davidson (1995) and Crostella & Backhouse (2000). Ages from Ogg et al. (2008). This study focused on the Leederville aquifer, and other aquifers are simplified.

Cretaceous

Rifting concluded in the Neocomian with the onset of seafloor spreading and extrusion of the Bunbury Basalt in the southern Perth Basin (Crostella & Backhouse 2000). Widespread thermally induced uplift and erosion created an unconformity between the syn-rift and post-rift strata (Stagg et al. 1999). During the Cretaceous, rising relative sea level and thermal subsidence in the central and southern portions of the Perth Basin created accommodation for post-rift deposition of the nearshore marine Warnbro Group and subsequently the fully marine Coolyena Group, separated by a disconformity or unconformity (figures 4 to 13) (Spring & Newell 1993; Crostella & Backhouse 2000; Miller et al. 2005). Local rifting continued along the Badaminna Fault System (Figure 3) from the Late Neocomian to the Aptian, resulting in the thickest deposits of the Warnbro Group in the Vlaming Sub-basin (Spring & Newell 1993; Crostella & Backhouse 2000).

Paleocene to Quaternary

The Cretaceous Warnbro and Coolyena groups were locally eroded during the Early Paleocene, notably in the south-west of the study area (Figure 14). The unconformably overlying Kings Park Formation (figures 4 and 14) is composed of shallow marine to estuarine strata that filled a drowned river valley or submarine canyon (Playford et al. 1976). This was followed by a period of non-deposition and erosion from the Eocene until the Pliocene (Figure 15). The superficial formations (figures 4 and 16) are a complex succession of shallow marine to terrestrial strata deposited on the Pliocene–Quaternary unconformity (Davidson 1995; Mory et al. 2005).

2.2 Warnbro Group

This section summarises the depositional and structural history of the Warnbro Group within the Gnangara groundwater system as presented by Leyland (2011). The group was divided by Leyland (2011) into five stratal packages through sequence stratigraphic analysis. This approach focuses on the correlation of *surfaces* that represent times or events, placing strata in a chronostratigraphic framework that describes the changing depositional conditions.

This is in contrast to previous lithostratigraphic correlation by Davidson (1995), as lithostratigraphy focuses on the physical characteristics or *lithology* of strata, rather than their relative age and chronostratigraphic significance. However the stratal packages proposed by Leyland (2011) correspond well to the equivalent lithostratigraphic units of Davidson (1995) and for simplicity and consistency with earlier literature, the stratal packages are referred to by their corresponding lithostratigraphic names.

The Warnbro Group was deposited from the Late Valanginian to Early Aptian, over a timeframe of ~15 to 20 million years (Figure 4). Leyland (2011) divided this period into five depositional sequences, controlled by the relative rise and fall of sea level. These sequences and the sea level curve are shown in figures 5 to 11 and discussed further in Leyland (2011).

Gage Formation (or stratal package, Kwg)

The sand-rich Gage Formation was deposited from Valanginian to Early Hauterivian in moderate energy marine conditions. The package is intersected by few bores and little is known about the depositional environment and relative sea level during deposition. Two depositional sequences were deposited in the Vlaming Sub-basin during the same period. Their distribution was influenced by the topography of the underlying unconformity (Spring & Newell 1993) and the Gage Formation represents the landward portions of these sequences.

South Perth Shale (stratal package, Kws)

A subsequent rise in relative sea level and a deepening of depositional conditions created a flooding surface at the base of the South Perth Shale. Relative sea level continued to rise during Late Valanginian to Early Hauterivian, during which time the mud-rich package was deposited from suspension on the lower shoreface or shelf (Figure 5) (e.g. Posamentier & Allen 1999). As a result the package fines upwards and thins to the north-east where the package is absent due to sediment bypass and erosion. Syn-depositional faulting occurred during this Late Valanginian to Early Hauterivian period. This caused thickening of the South Perth Shale to the south-west of the Wanneroo and Serpentine Faults (Figure 5).

Mariginiup Member (or stratal package, Kwlm)

The highest level of relative sea level and the deepest marine depositional conditions occurred at the end of deposition of the South Perth Shale. There was then a fall in relative sea level during the Early Hauterivian deposition of the Mariginiup Member. The package was deposited as mud-rich, delta front bars which prograded west into the basin (Figure 6). The bars formed at the mouth of delta distributaries until flow was diverted into a new channel (distributary switching), at which point the bar would be abandoned and a new one formed nearby.

Progradation of the delta front caused the package to coarsen upwards overall (e.g. Bhattacharya 2006). The package thins to the north-east where coeval delta top deposits may have been deposited (Figure 6). There was limited fault movement during this period, and as a result there is minimal variation in thickness of the Mariginiup Member.

Wanneroo Member (or stratal package, Kwlw)

Before deposition of the Late Hauterivian Wanneroo Member, there was an abrupt and regional shallowing of depositional conditions. This was accompanied by an influx of river-borne sediment from the north-east, resulting in delta plain deposition of the heterolithic Wanneroo Member. A tide influenced lower delta plain covered most of the study area, while a fluvial upper delta plain was restricted to the eastern margin of the basin (Figure 7).

The fluvial upper delta plain was fed by a mixed load (suspended and bedload) river system (e.g. Reading & Collinson 1996). Crevasse splays and floodplain silts were deposited after channel avulsion, and channel-fill sand bodies were deposited during lateral migration of the channel belt (e.g. Reading & Collinson 1996; Bridge 2006). On the tidal lower delta plain, the interdistributary bays were filled by intertidal and subtidal flats, and tidally influenced channel-fill sand bodies were deposited during lateral migration of the distributaries (e.g. McIlroy 2004; Ponten & Plink-Bjorklund 2007; Mangano & Buatois 2004).

During deposition of the Wanneroo Member the sea level fell, causing erosion of 30 to 50 m deep distributary valleys (Figure 8). As the sea level fell, valley incision moved landward from west to east. In the west, where valleys were incised, sediment was not deposited and bypassed the study area (e.g. Willis & Gabel 2003). To the east there remained an active fluvial delta plain (Figure 8). As relative sea level began to rise, the distributary valleys were then filled with channel-fill deposits, creating sand bodies that extend laterally over 5 to 10 km (Figure 9).

There was syn-depositional extensional movement along the Badaminna, Darling, Wanneroo and Serpentine faults during the Late Hauterivian. This caused thickening of the Wanneroo Member to the west and south-west of these faults (figures 7, 10).

Pinjar Member (or stratal package, Kwlp)

A subsequent rise in relative sea level and a deepening of depositional conditions created a flooding surface at the base of the Pinjar Member. A prograding wave-influenced delta with sediment supply from the east was then deposited from the Barremian to Early Aptian (Figure 11). Bedload sands were deposited close to the eastern margin and reworked into a sand-rich shoreline, creating deposits of prograding shoreface sands along the eastern margin of the basin. Suspended silt and fine sands were carried beyond the shoreline to be deposited as silt-rich offshore mouth bars, creating deposits of stacked, prograding silt-rich bars across the rest of the study area. In the intermediate zone intercalated mud and sand facies were deposited on the lower shoreface.

There was syn-depositional extensional movement along the Badaminna, Darling, Wanneroo and Serpentine faults during Barremian to Early Aptian. This caused thickening of the Pinjar Member to the west and south-west of these faults (Figure 11). There was possibly a further sea level rise during the Late Barremian to Early Aptian causing a minor landward shift in facies which is preserved in the south-east of the study area. This was followed by erosion of the Pinjar and locally the Wanneroo members. This created an intra-Aptian unconformity which marks the top of the Warnbro Group (Figure 12).

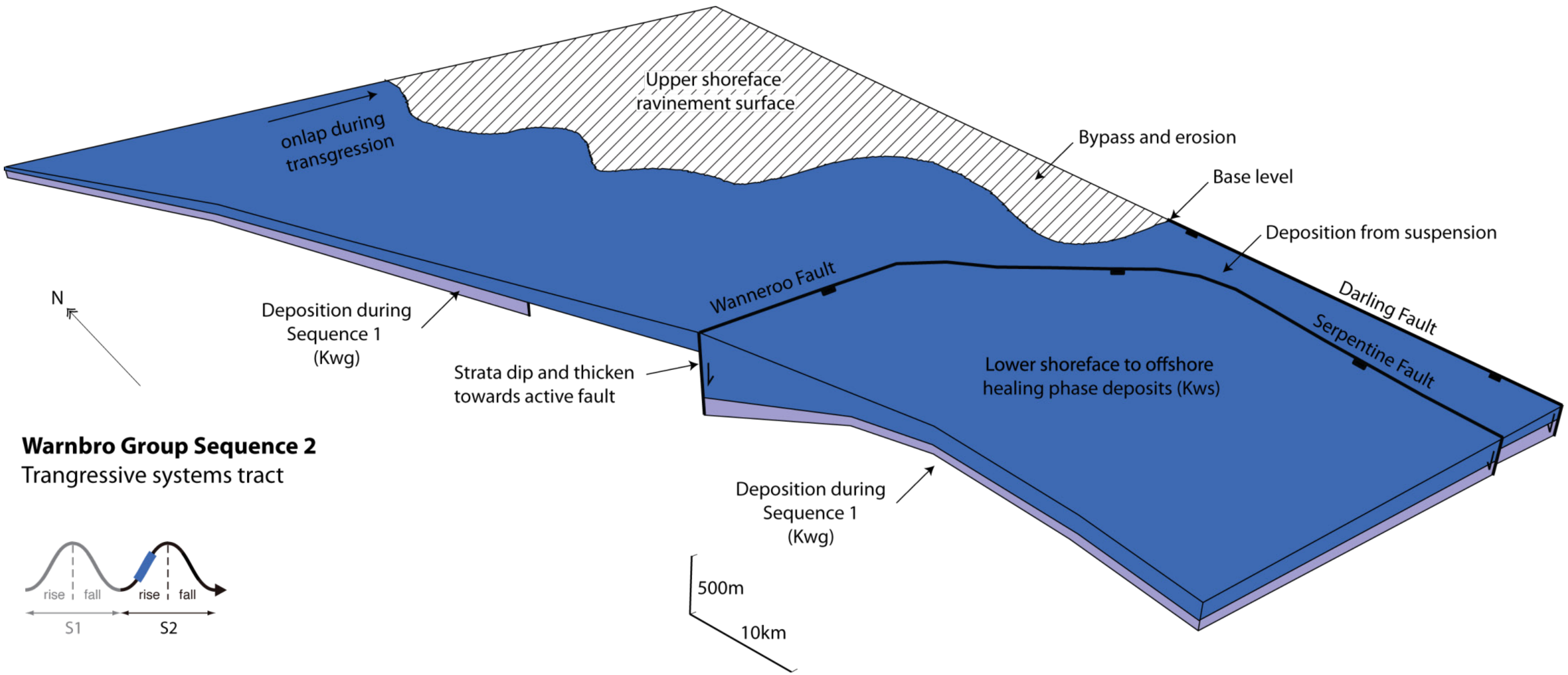


Figure 5 Block model showing deposition of the South Perth Shale. Sediment bypass and erosion occurs on the upper shoreface, and the mud rich strata are deposited from suspension in the lower shoreface to offshore zone. Strata thicken towards active faults.

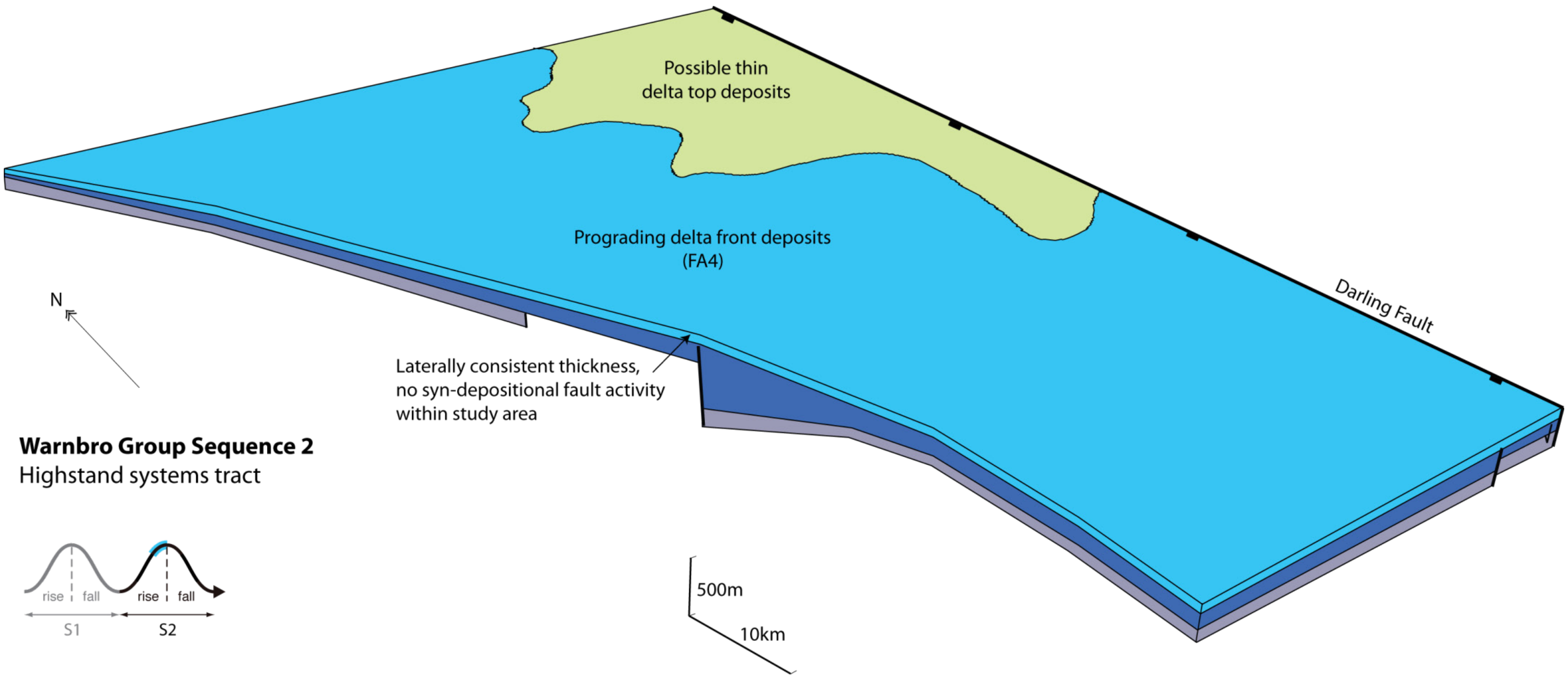


Figure 6 Block model showing deposition of the Mariginiup Member. There is widespread delta front deposition of prograding mouth bars, with bypass or minor delta top deposition in the north-east.

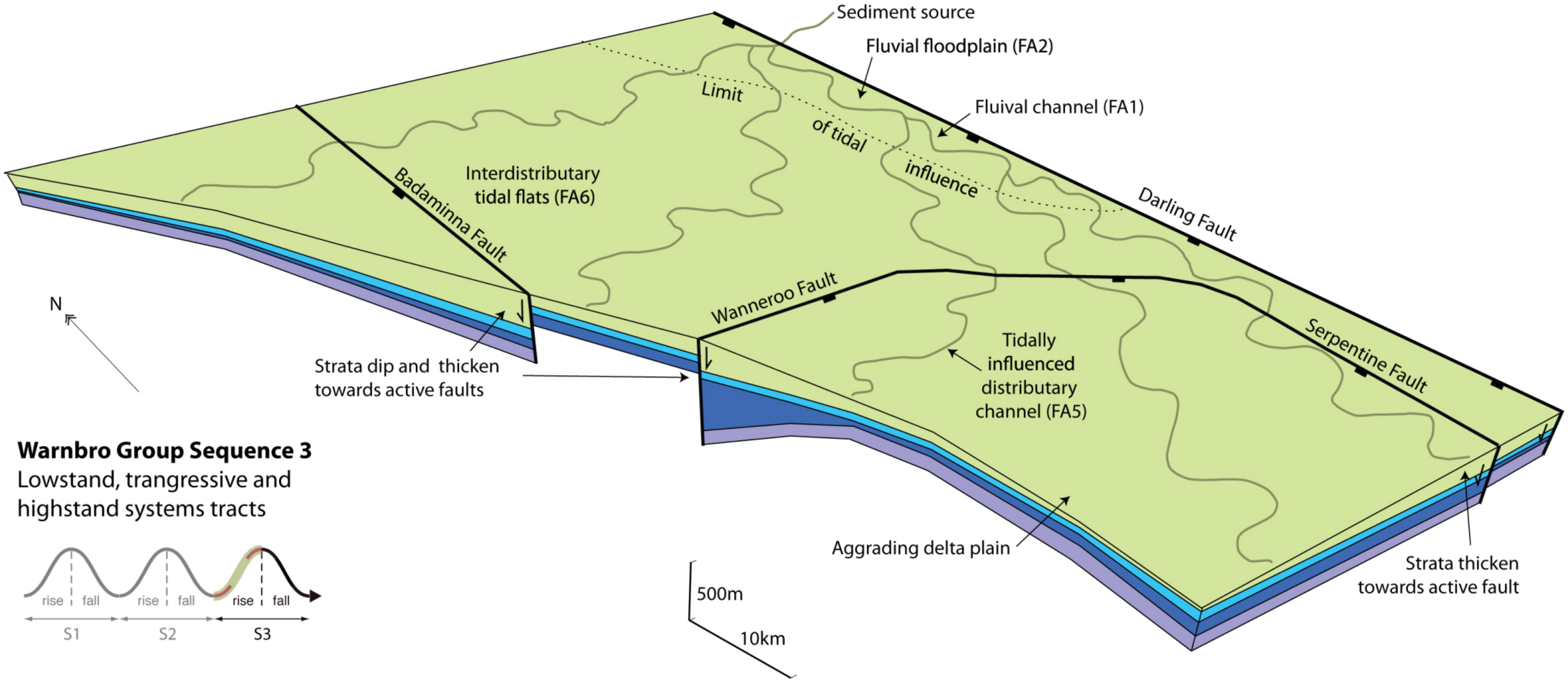


Figure 7 Block model showing deposition of the lower part of the Wanneroo Member. Deposition occurs on an aggrading delta plain with widespread tidal conditions and with fluvial conditions restricted to the eastern margin of the basin. Strata thicken towards active faults.

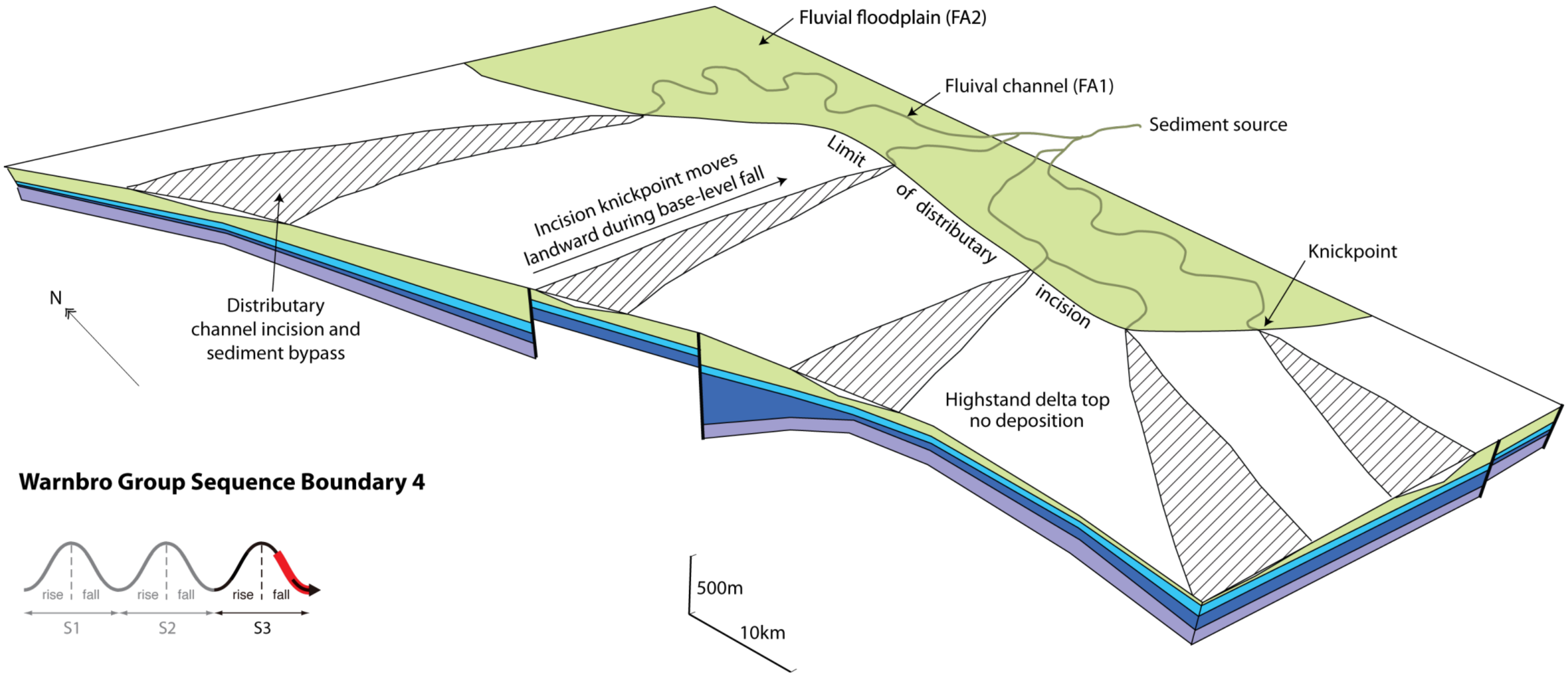


Figure 8 Block model showing the regression surface within the Wanneroo Member. This surface features distributary incision due to base level fall, leading to sediment bypass of the delta plain, although fluvial deposition continues landward of the limit of distributary incision.

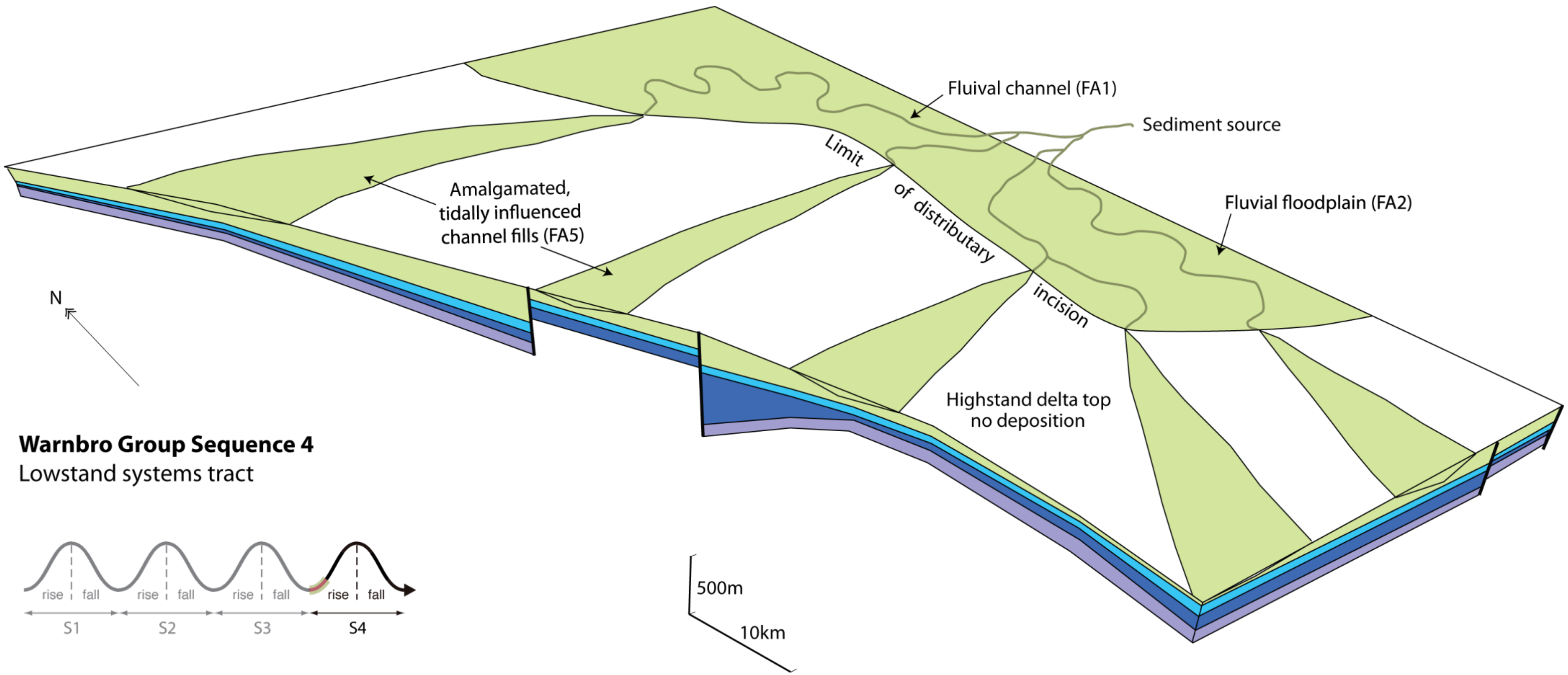


Figure 9 Block model showing deposition of the middle part of the Wanneroo Member. Amalgamated channel-fill deposits infill the incised distributary valleys. Fluvial deposition continues landward of the limit of distributary incision.

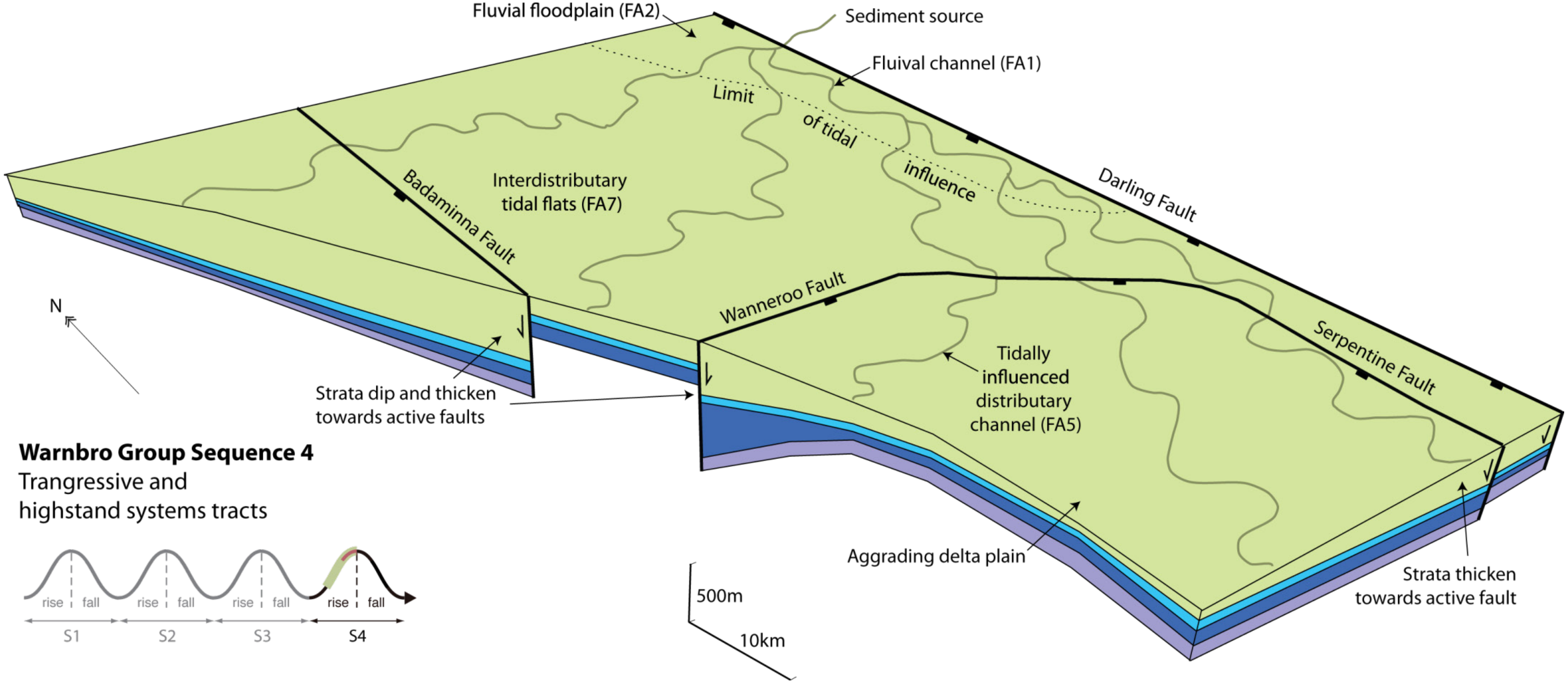


Figure 10 Block model showing deposition of the upper part of the Wanneroo Member. Deposition occurs on an aggrading delta plain, with widespread tidal conditions and fluvial conditions restricted to the eastern margin of the basin. Strata thicken towards active faults.

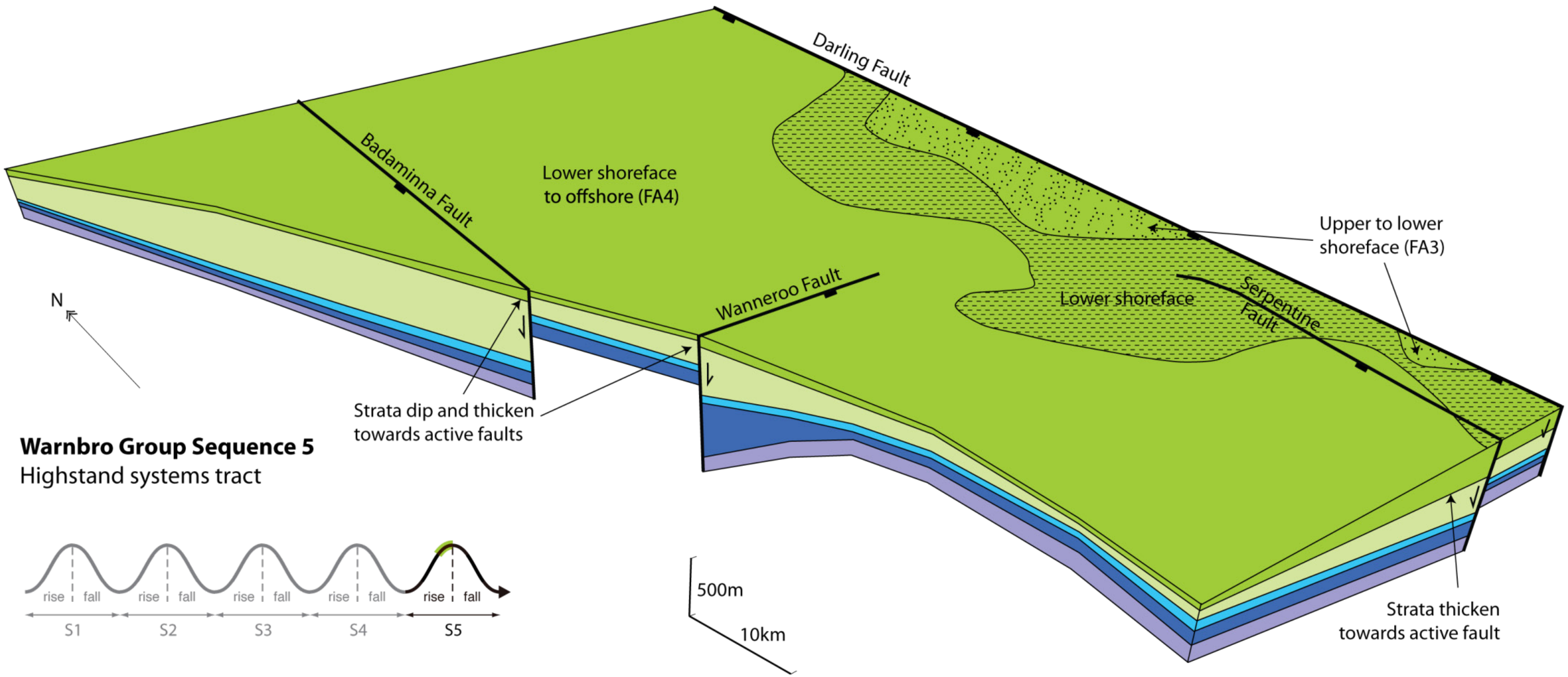


Figure 11 Block model showing deposition of the Pinjar Member. There is widespread offshore deposition while shoreface sands restricted to the eastern margin of the basin. Strata thicken towards interpreted active faults.

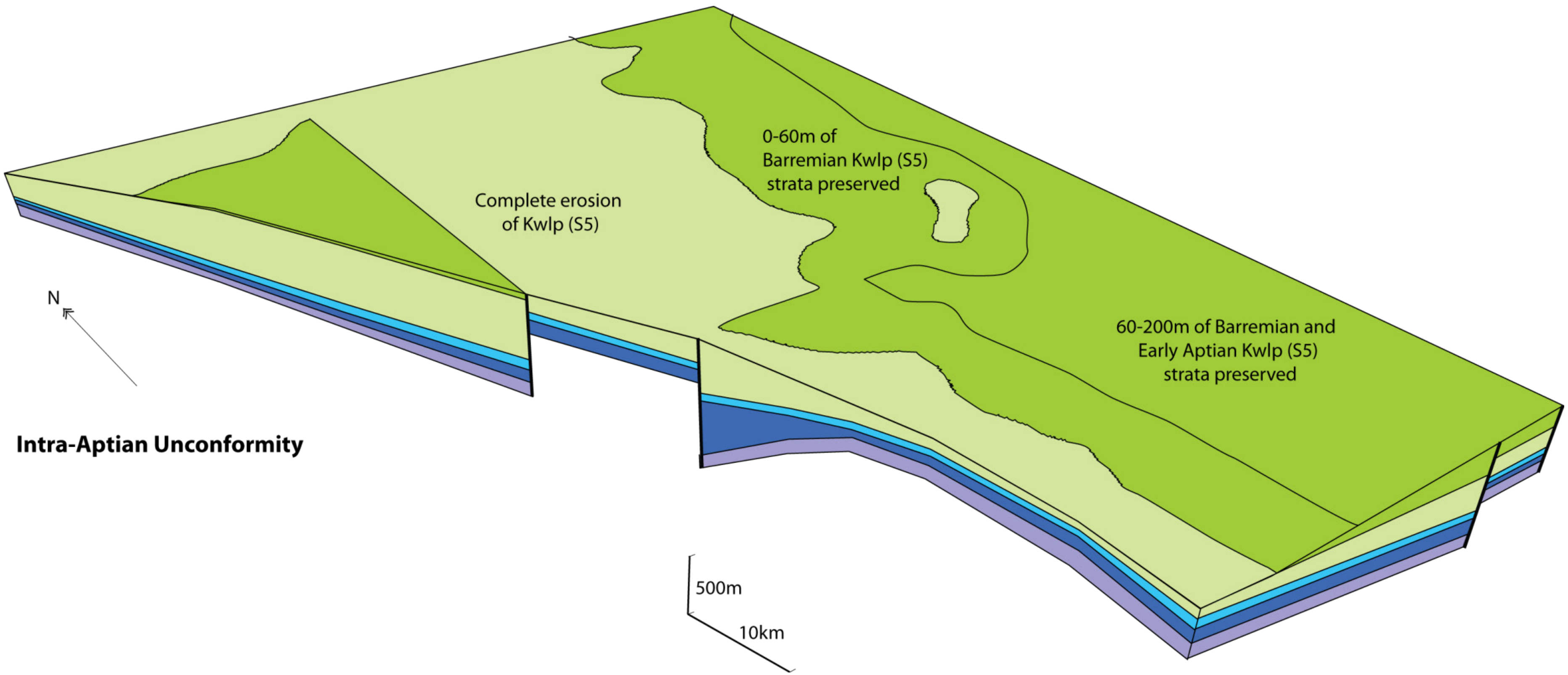


Figure 12 Block model showing the Intra-Aptian unconformity and partial to complete erosion of the Pinjar Member.

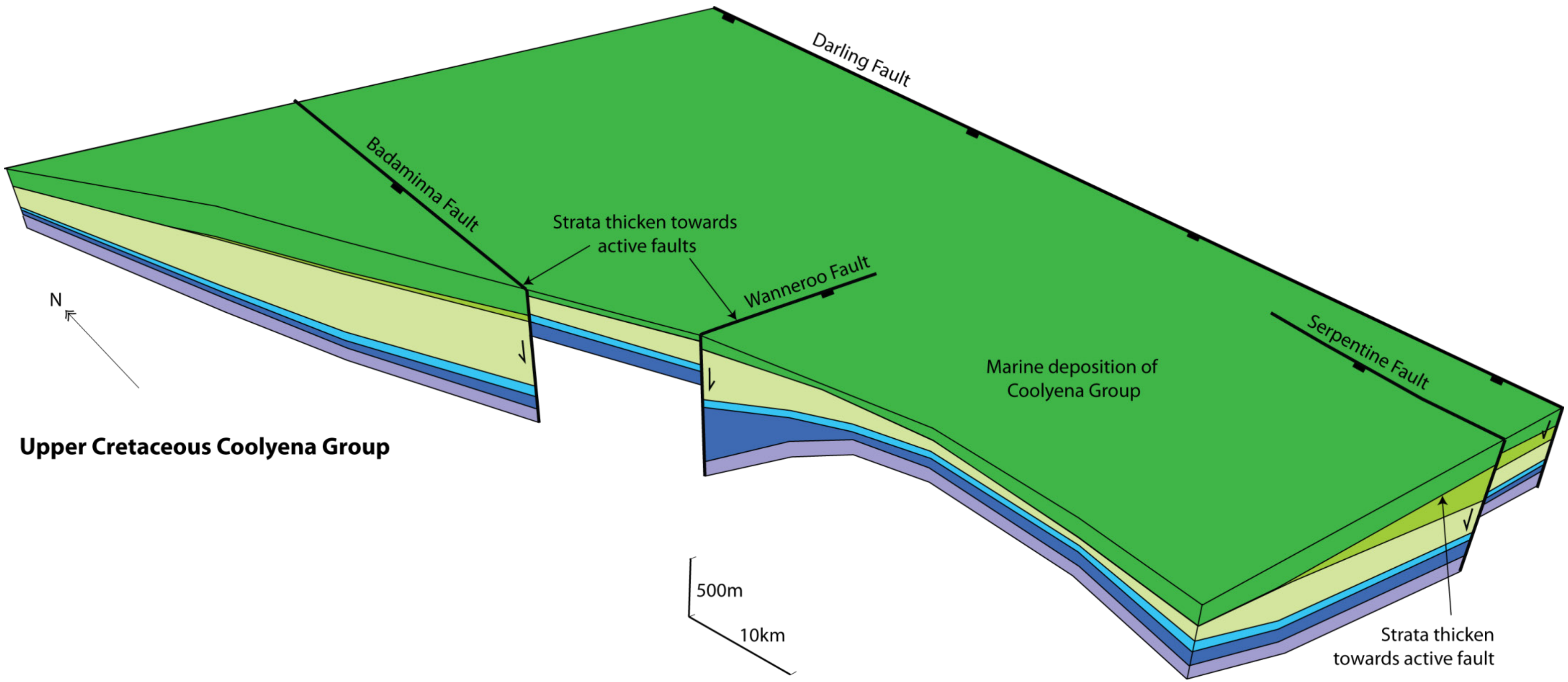


Figure 13 Block model showing the Upper Cretaceous Coolyena Group, deposited in predominantly marine conditions (Crostella & Backhouse, 2000). Lateral variations in strata thickness are interpreted in this study to represent Late Cretaceous syn-depositional fault movement.

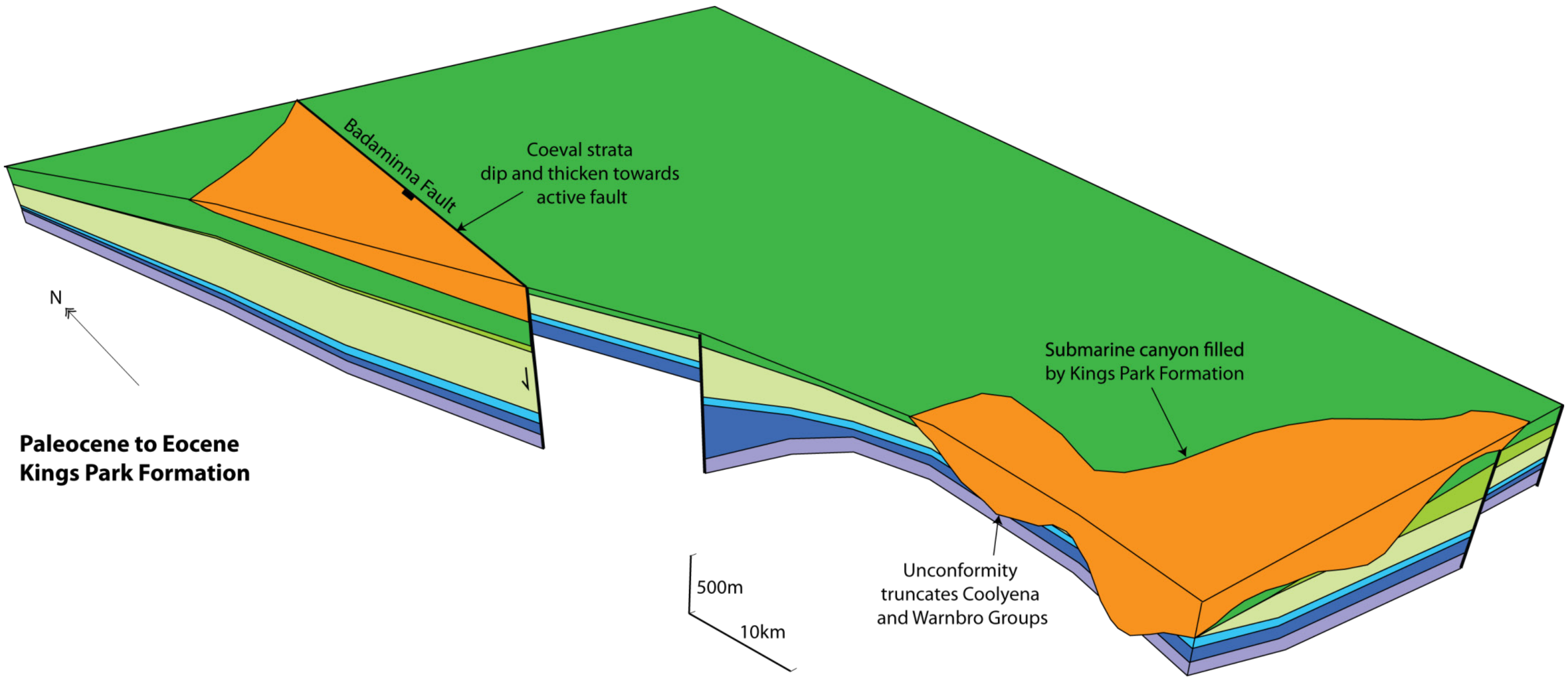


Figure 14 Block model showing the Paleocene to Eocene King Park Formation. The west-plunging valley-shaped unconformity was interpreted by Playford et al. (1976) as a sub-marine canyon later filled by the Kings Park Formation, and the coeval strata in the northwest are interpreted in this study to represent syn-depositional movement on the Badaminna Fault.

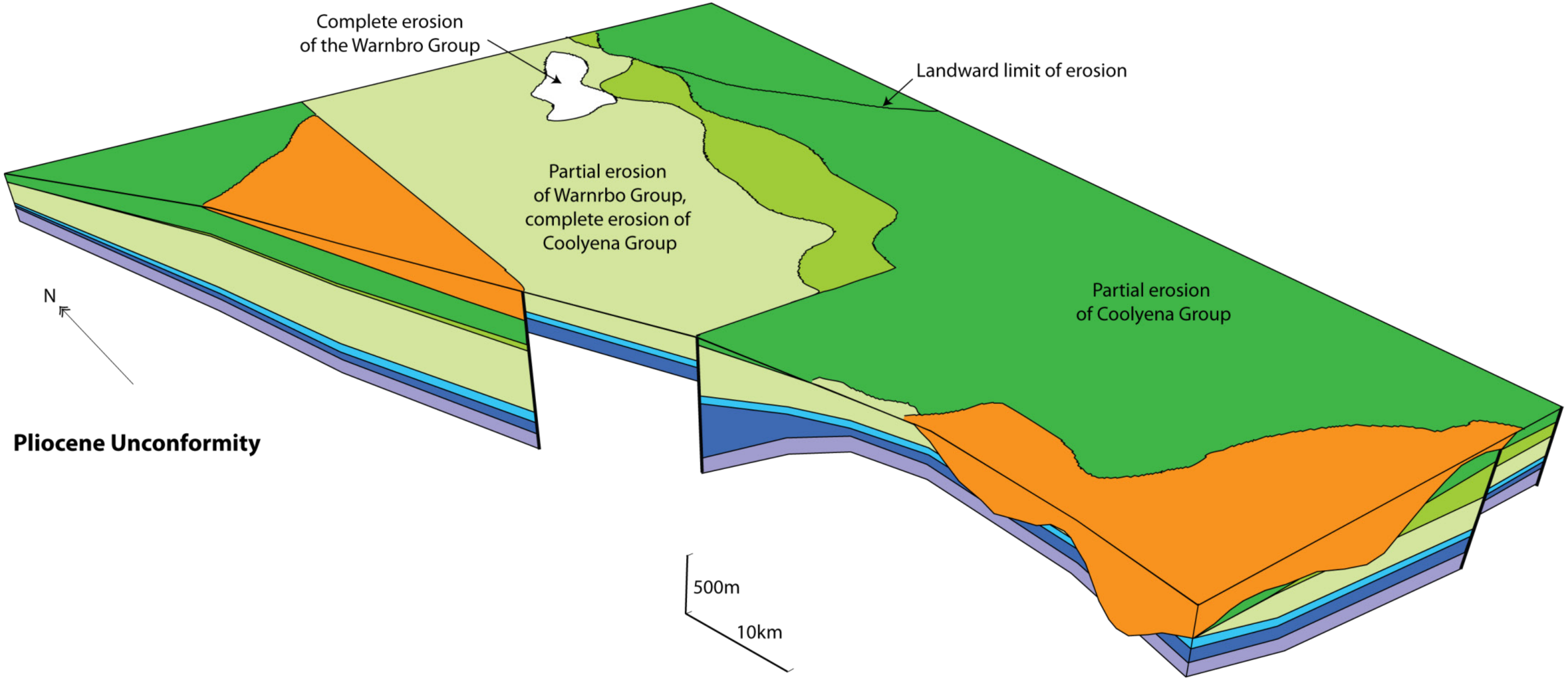


Figure 15 Block model showing the Pliocene unconformity, featuring significant erosion of the Warnbro and Coolyena groups. A topographic high in the northeast is beyond the landward limit of erosion (Playford et al. 1976).

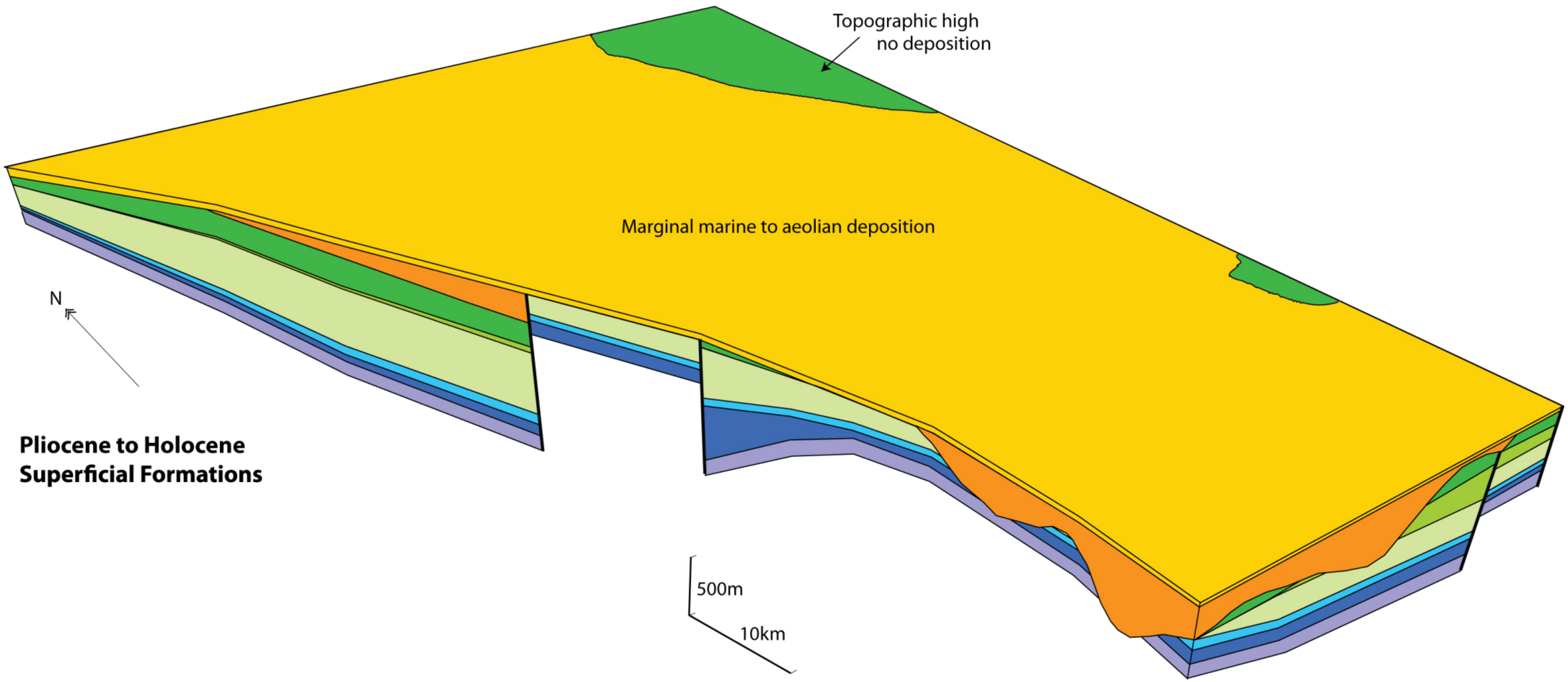


Figure 16 Block model showing the marginal marine to aeolian Pliocene to Holocene superficial formations (Davidson 1995)

3 Sedimentary geology

3.1 Introduction

This chapter describes the geology and gamma ray motifs of the Warnbro Group, focusing on the Mariginiup, Wanneroo and Pinjar members that host the Leederville aquifer. This chapter also describes the primary depositional connectivity of the sand-rich strata within the Leederville aquifer.

Depositional setting and facies associations

The Leederville Formation was deposited in a tidally influenced, deltaic depositional setting, with sediment influx from the east or north-east (Figure 17). Earlier work by Backhouse (1988) and Spring & Newell (1993) also indicated a fluvio-deltaic setting. The deltaic setting is made up of seven individual depositional environments, each of which is represented by a different facies association (FA1 to FA7). The fluvial upper delta plain is composed of channel fill (FA1) and flood plain deposits (FA2). The tidally influenced lower delta plain is composed of tidal flats deposits that form interdistributary bays (FA6 – intertidal, FA7 – subtidal), with distributary channel fill and incised distributary valley-fill deposits (FA5). The tidally influenced delta front is composed of prograding bars (FA4). The wave influenced shoreface is represented by prograding shoreface sands (FA3).

Each facies association is characterised by distinctive sedimentary features and gamma ray log motifs, which are summarised in Appendix A. This appendix can be used to recognise depositional environments in drill cores and on downhole logs.

Stratal packages and lithostratigraphic units

The Warnbro Group was divided by Leyland (2011) into five distinct stratal packages through sequence stratigraphic analysis, and the strata depth for each borehole are presented in Appendix B. As discussed in Section 2.2, this approach focuses on the correlation of *surfaces* that represent times or events, placing strata in a chronostratigraphic framework. It incorporates lateral variation in facies and gamma ray log motif within stratal packages. This is in contrast to previous lithostratigraphic correlation by Davidson (1995), which was based on the *lithology* or physical characteristics of strata. However these stratal packages correspond well to the lithostratigraphic units described by Davidson (1995), and for simplicity and consistency with earlier literature, the lithostratigraphic nomenclature is retained.

In this report, more detailed descriptions are presented, in particular the lateral variation in facies and gamma ray motif within the Wanneroo and Pinjar members. In some places this recognition of lateral variation has led to correlation differences between this report and Davidson (1995) for the Wanneroo and Pinjar members. This is especially true in the east of the study area.

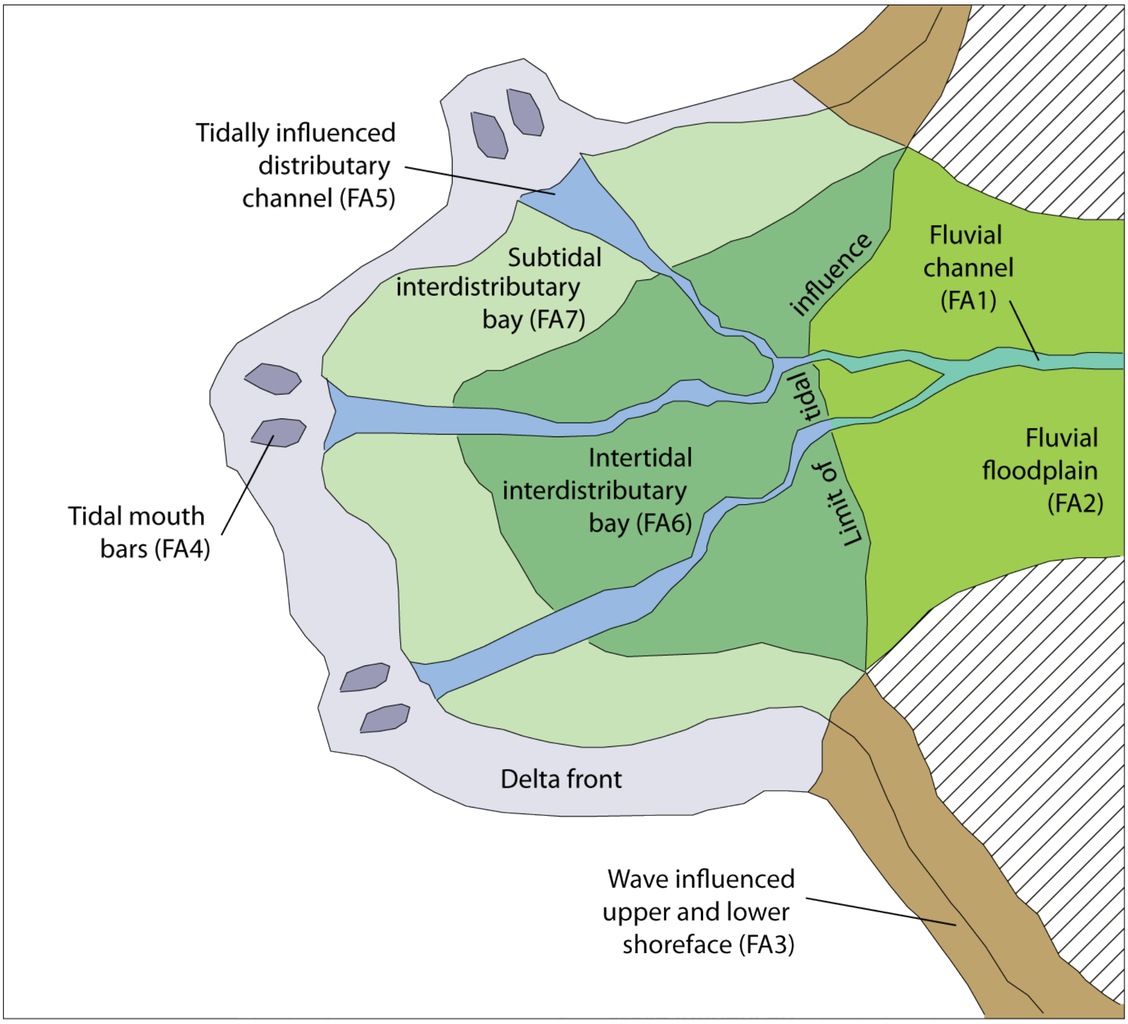


Figure 17 Sketch showing the overall depositional setting of the Leederville Formation, incorporating a fluvial upper delta plain (FA1, FA2), a tidally influenced lower delta plain (FA5–FA7), a tidally influenced delta front (FA4) and a shoreface (FA3). Not shown are the incised distributary valley fills represented by 30 to 50 m thick intervals of FA5.

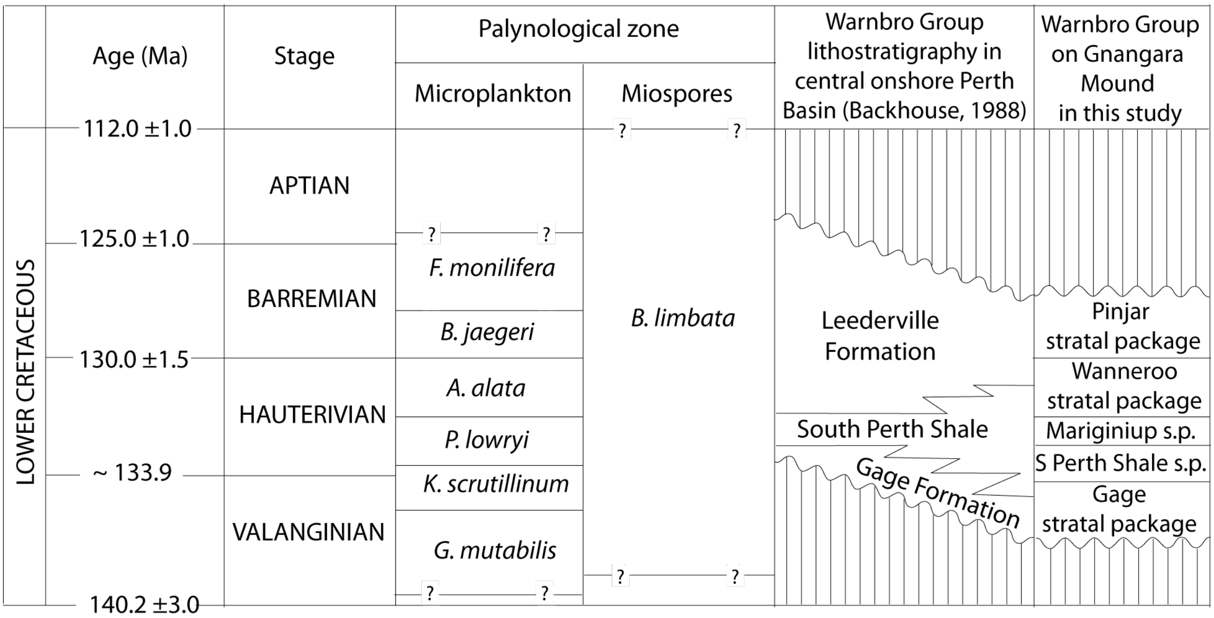


Figure 18 Biostratigraphy of the Warnbro Group in the central onshore Perth Basin, modified from Backhouse (1988), and for the Gnangara groundwater system based on 11 reports from Backhouse (2005). Absolute ages from Ogg et al. (2008).

Biostratigraphic zones

The age of strata within the Warnbro Group is determined by palynological analysis. Two parallel palynological zonations are used, one based on miospores and the other on microplankton (Backhouse 1988). Within the Warnbro Group, microplankton display a greater vertical variation than miospores and six microplankton zones (*G. mutabilis, K. scrutillinum, P. lowryi, A. alata, B. jaegeri* and *F. monilifera)* are recognised within the range of the *B. limbata* miospore zone (Figure 18). Palynological reports written before 1982 do not use these biostratigraphic zones, but resolution is sufficient to identify the top and base of the Warnbro Group. Of the 82 palynological reports relevant to the Gnangara groundwater system, eleven (for bores AM01, AN02A, AM18A, AM33A, AM34A, AM35A, AM36, AM37A, AM38A, BNYP 1/07 and Q37) subdivide the Warnbro Group into microplankton zones.

Paleoenvironmental conditions are interpreted in these reports from a combination of palynomorph diversity, the paleoecology of the species represented and the relative proportions of marine and non-marine palynomorphs. Palynomorphs are especially important as paleoenvironmental indicators in the Early Cretaceous Perth Basin due to the rarity of other hard fossil groups (Backhouse 1988).

Gamma ray log motifs

In siliciclastic sedimentary rocks, variations in gamma ray count are caused by changes in proportions of mud and sand. Radioactive potassium-rich clay minerals tend to be concentrated in silt and clay, resulting in a higher gamma ray count than from the less radioactive sand (Rider 2002). Consequently, minimum (low) and maximum (high) gamma ray counts represent 100% sand and 100% mud. A synthetic log of sand percentage was generated for each gamma ray log in this study and then gamma ray logs were coloured by sand percentage (Leyland 2011). Very high gamma ray counts, outside the usual range, are generated by the presence of the radioactive accessory minerals glauconite, zircon and monazite (Leyland 2011).

In the Leederville Formation, downhole gamma ray logs exhibit contrasting gamma ray motifs for different facies associations. This allows interpretation and correlation of depositional environments using downhole gamma ray logs. The primary influence on the gamma ray motif is the thickness and vertical distribution of sand-rich (>80% sand) intervals in different facies associations. This controls the distribution of low radiation intervals.

Depositional connectivity

There are three major depositional controls on connectivity: sand/silt ratio, sand body dimensions and geometry; and sand body distribution (Ainsworth 2005). The sand content of each facies association is based on the silt/sand ratios observed in core (Leyland 2011), and the lateral variation in sand percentage across the study area is based on sand percentage calculations from downhole gamma ray logs. This sand percentage distribution is reliable as a description of the relative magnitude of hydraulic parameters, but should not be used to calculate absolute values (Leyland 2011). Sand body dimensions and their distribution are based on comparison with similar deposits and on global sand body databases (e.g. Gibling 2006).

3.2 Gage Formation

Geology

The Gage Formation (Kwg) is composed of sand dominated, locally mud-rich facies deposited in moderate energy, restricted to open marine conditions. Within the study area the package corresponds to the *G. mutabilis* to *K. scrutillinum* palynological zones (Figure 19, Valanginian to Early Hauterivian). The package is typically ~100 m thick, and is present throughout most of the study area, except in the north-eastern corner and a small area in the central west (Figure 20a).

Gamma ray motif

The package is intersected by few bores and the observed motifs are variable. Gamma ray count is typically low, with locally high to very high gamma ray count (figures 19 and 21). The base of the package is typically difficult to identify due to its similarity with the underlying Yarragadee Formation, in which case palynological analysis is required.

3.3 South Perth Shale

Geology

The South Perth Shale (Kws) is composed of mud-rich facies that fine upwards overall. The package was deposited in gradually deepening, open marine conditions. Within the study area the package corresponds to the *K. scrutillinum* to *P. lowryi* palynological zones (Figure 19, Late Valanginian to Early Hauterivian). The package is typically ~100-300 m thick and is present throughout most of the study area except in the north-eastern third (Figure 20b).

Gamma ray motif

The gamma ray motif is dominated by high gamma ray count which increases upwards overall and has a blocky, finely serrated character (figures 19 and 21). The base of the package is marked by a sharp change from low to high gamma ray count.

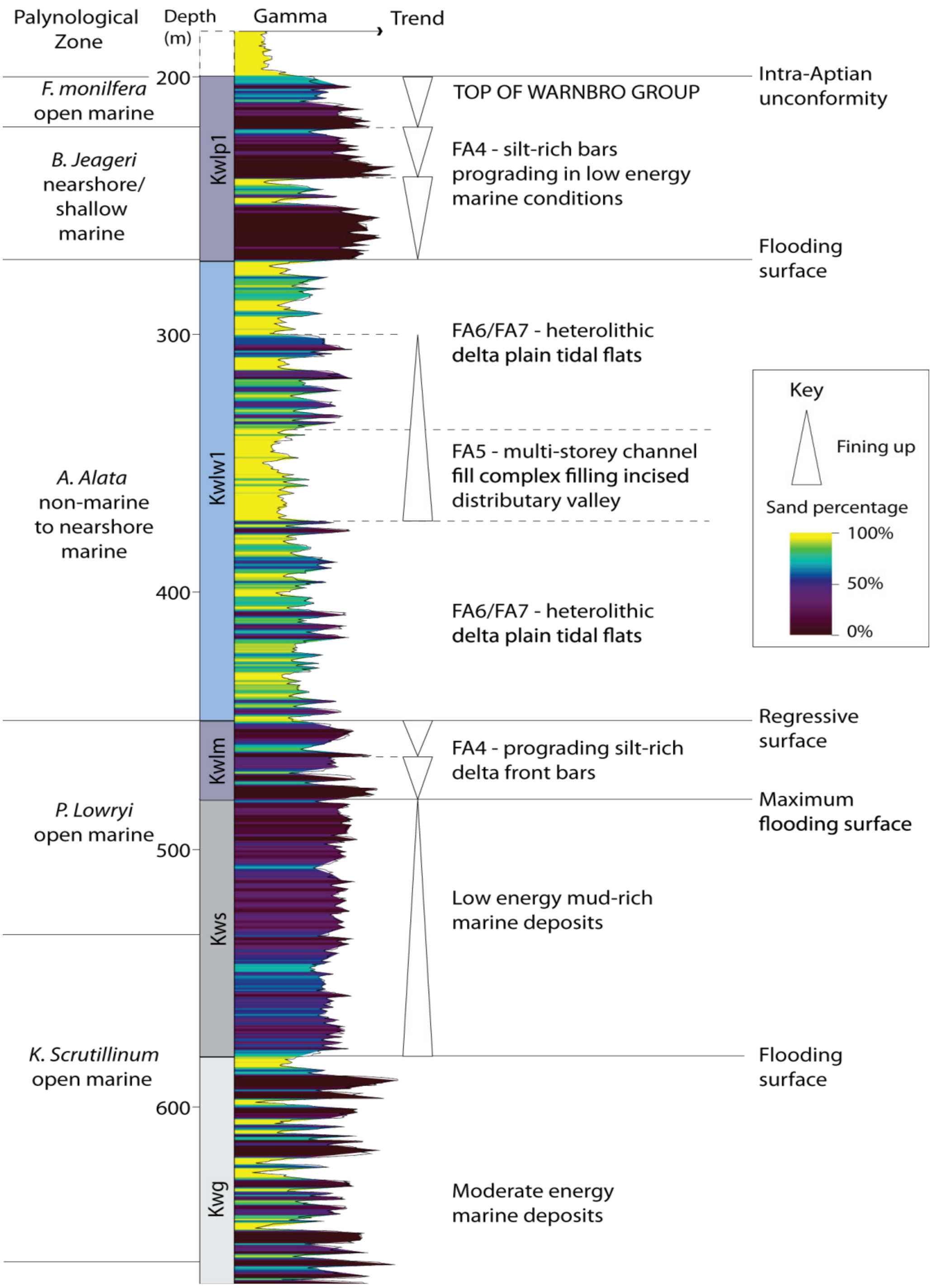


Figure 19 Representative downhole log with sand percentage colour scheme showing stratal surfaces and interpreted trends of the Warnbro Group. Palynological zones are from 11 reports from Backhouse (2005). Example log is Mirrabooka 1 (see Figure 21), depth in metres below ground surface.

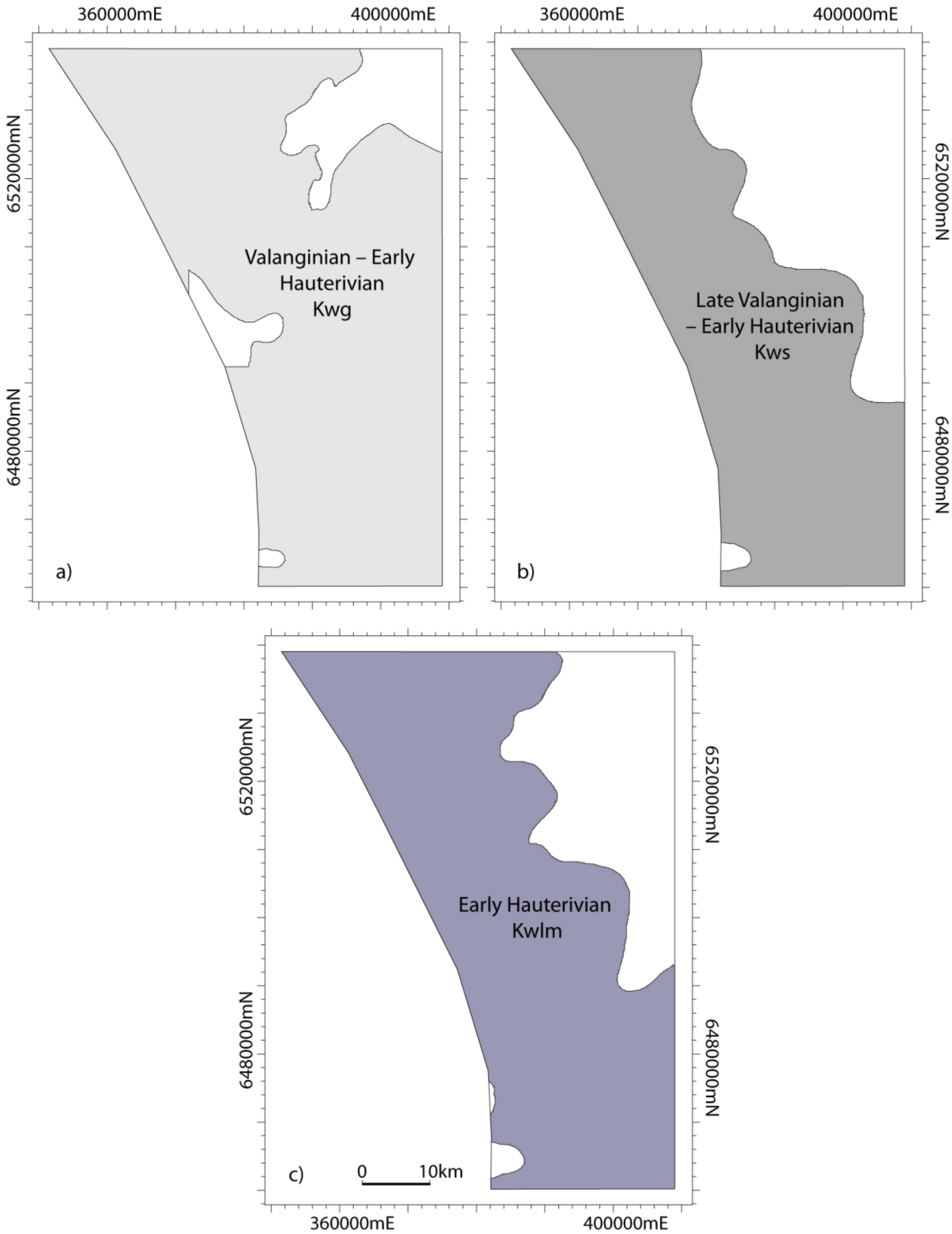


Figure 20 Distribution of (a) Gage Formation, Kwg, (b)South Perth Shale, Kws, (c) Mariginiup Member, Kwlm. The strata are present across the study area except in the north-east.

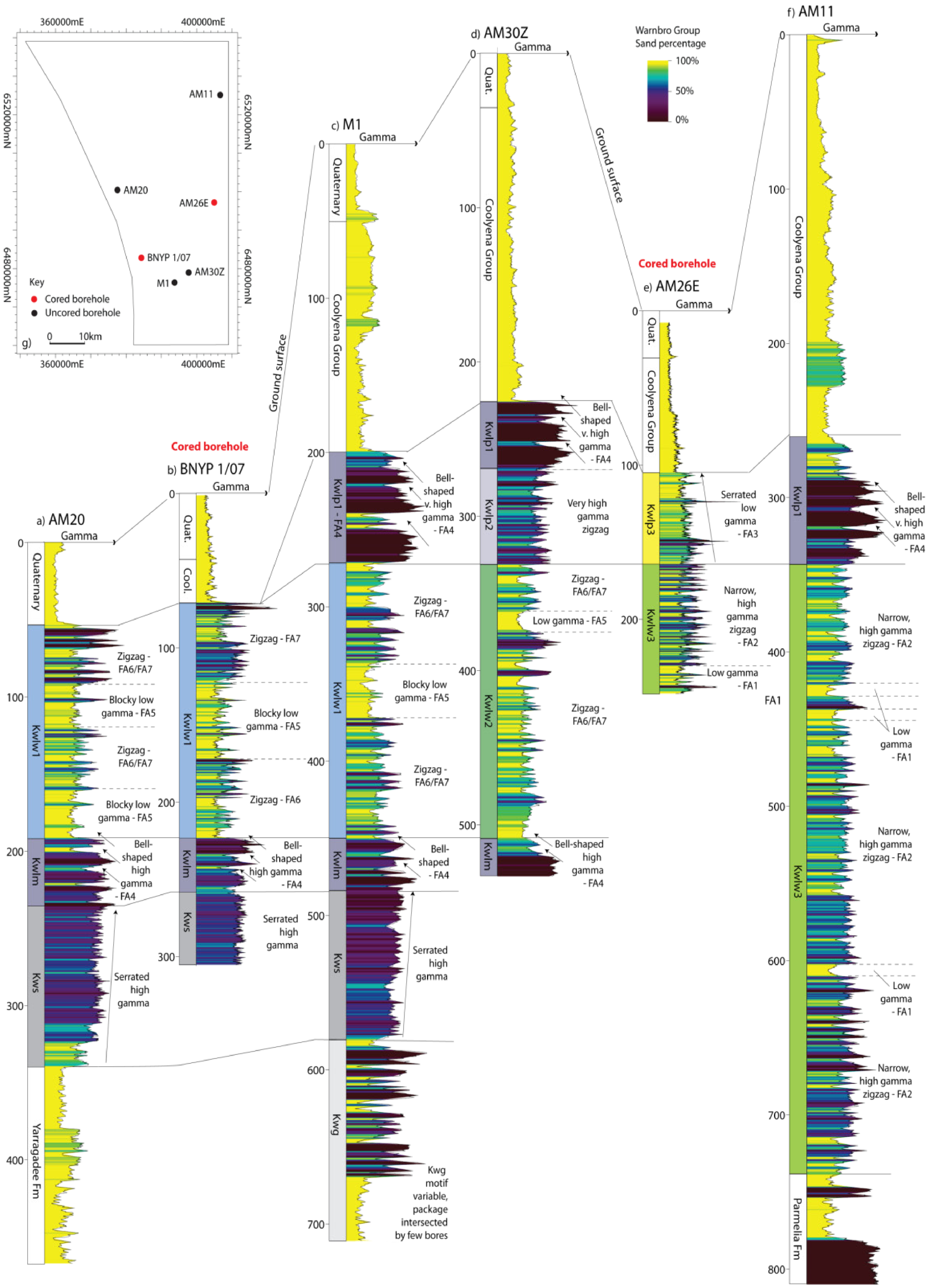


Figure 21 Selected logs showing typical gamma ray motifs and equivalent facies associations of the Warnbro Group. The colour scheme represents sand percentage for the Warnbro Group and is not valid for other strata. (a) AM11, (b) AM26E, (c) AM20, (d) BNYP 1/07, (e) AM30Z, (f) Mirrabooka 1 (g) map showing bore locations. Depths in metres below ground surface.

3.4 Mariginiup Member

Geology

The Mariginiup Member (Kwlm) is composed of 10 to 30 m thick, sharp-based intervals of silt-rich facies that coarsen upwards with locally sandy tops. These intervals were deposited as stacked, prograding delta-front tidal bars (FA4, figures 17 and 19) in low energy, nearshore to open marine conditions at the mouth of distributaries (e.g. Bann & Fielding 2004; McIlroy 2004). The stack coarsens upwards overall, due to increasing energy conditions. Within the study area the package corresponds to the *P. lowryi* palynological zone (Figure 19, Early Hauterivian). The package is typically ~50 m thick and is present throughout most of the study area except in the north-eastern corner (Figure 20c).

Gamma ray motif

The gamma ray motif is composed of 10 to 30 m thick, sharp-based, stacked, bell-shaped intervals dominated by high gamma ray count (figures 19 and 21). In each interval gamma ray count decreases upwards to moderate, locally low gamma ray count. The motif is locally blocky with 10 to 30 m scale intervals of high and low gamma ray count. Overall, the motif is typically composed of one to three stacked bell-shaped intervals, over which gamma ray count gradually decreases upwards. The base of the package is marked by a peak in gamma ray count, where the increasing trend of the Kws package changes to the decreasing trend of the Kwlm package (Figure 19).

Depositional connectivity

The Mariginiup Member does not contain any sand-rich strata, and acts as an aquitard. The lateral distribution of the package coincides with that of the South Perth Shale, and together they act as an aquiclude between the Leederville and Yarragadee aquifers.

3.5 Wanneroo Member

The Wanneroo Member (Kwlw) is composed of sand-rich and heterolithic facies deposited on a delta plain in nearshore-marine to non-marine conditions (Figure 19). Across most of the study area the package was deposited on a tide influenced, lower delta plain. Along the eastern margin of the basin, beyond the limit of tidal influence, the package was deposited on a fluvial, upper delta plain. The geology and gamma ray motif of the package varies laterally and the study area is divided into three distinct sections: west, centre and east (Figure 22a). The package is typically ~100 to 400 m thick and is present throughout most of the study area except a small window in the central north (Figure 22). Within the study area the package corresponds to the *A. alata* palynological zone (Figure 19, Late Hauterivian).

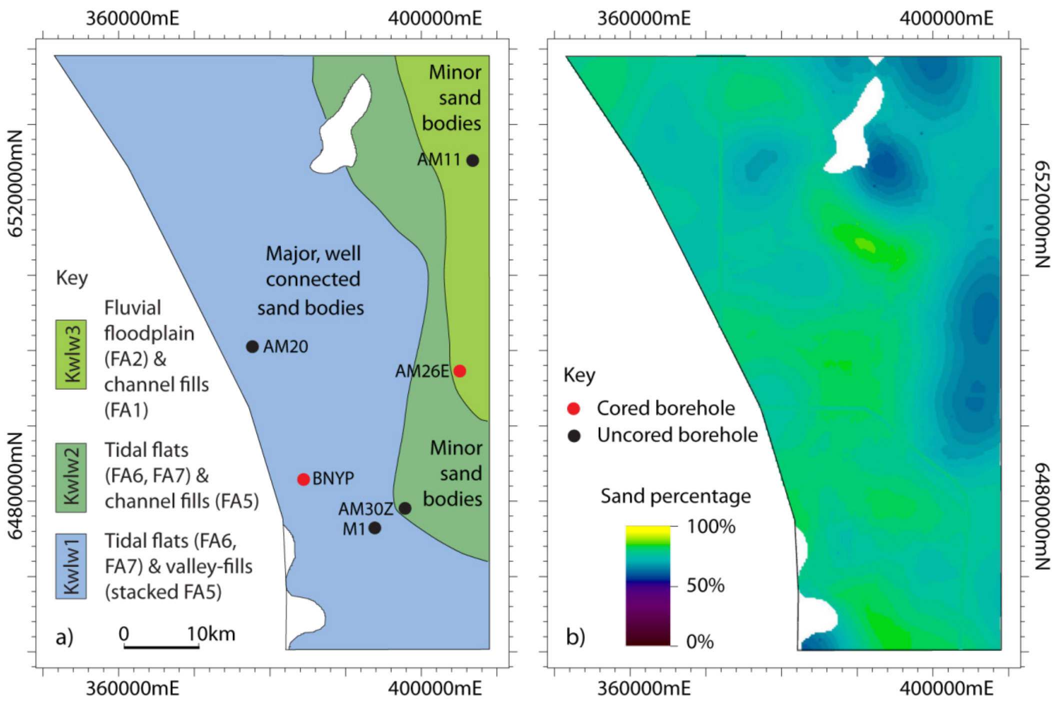


Figure 22 Facies architecture and sand percentage of the Wanneroo Member with the location of downhole gamma ray logs from Figure 21. (a) West, central and east sections, (b) average sand percentage calculated from gamma ray logs.

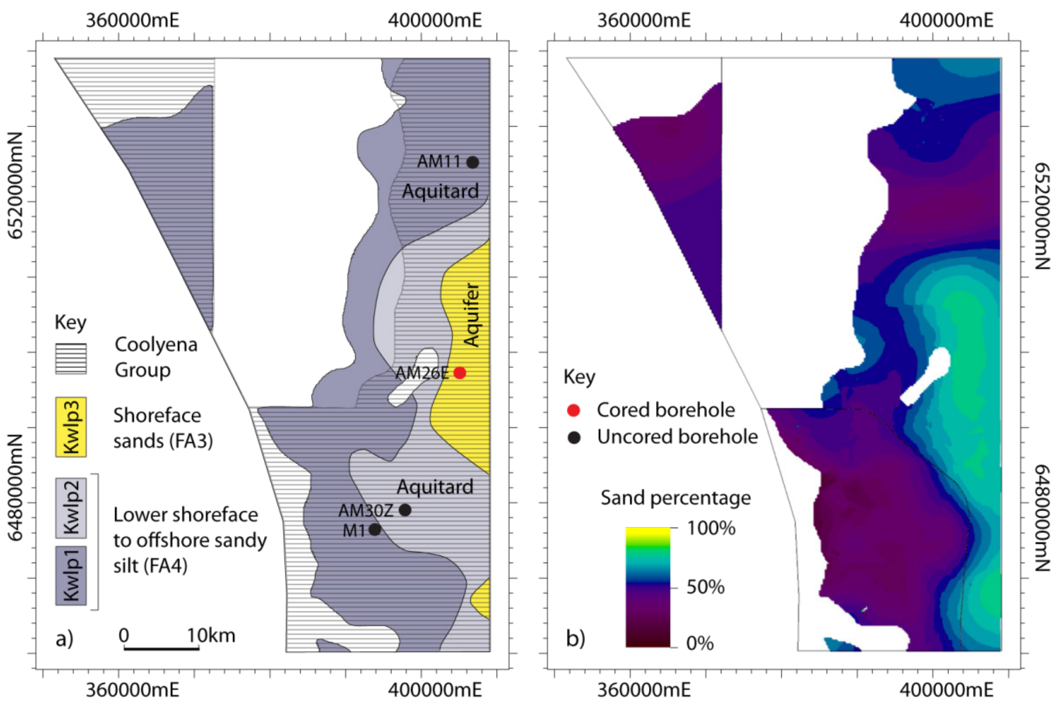


Figure 23 Facies architecture and sand percentage of the Pinjar Member with the location of downhole gamma ray logs from Figure 21. (a) West, central and east sections, (b) average sand percentage calculated from gamma ray logs.

a) West

Geology

The western section of the Wanneroo Member (Kwlw1) is composed of intercalated intervals of sand-rich channel-fill deposits (FA5) and heterolithic tidal flat deposits (FA6 and FA7, figures 17 and 19). These facies associations were deposited on the tidally influenced lower delta plain, and are well developed across the west of the study area (Figure 22a).

The package is dominated by 10 to 50 m thick intervals of sand-rich facies that were deposited in simple channel-fill complexes (FA5, 10 to 30 m thick) or multi-storey valley-fill complexes (FA5, 30 to 50 m thick). Simple channel-fill complexes were deposited by delta distributaries migrating across the delta plain (e.g. McIlroy 2004; Ponten & Plink-Bjorklund 2007). Multi-storey valley-fill complexes were deposited in distributary valleys that were incised into the delta plain after a fall in relative sea level (e.g. Bowen & Weimer 2003; Willis & Gabel 2003; Bhattacharya & Tye 2004).

These sand-rich intervals are intercalated with 10 to 40 m thick intervals of heterolithic facies. These heterolithic facies were deposited on tidal flats (FA6 and FA7) that formed in interdistributary bays on the delta plain (e.g. Mangano & Buatois 2004; Ponten & Plink-Bjorklund 2007).

Gamma ray motif

The western gamma ray motif is a composite motif made up of two characteristic intervals (figures 19 and 21). The sand-rich facies (FA5) are represented by 10 to 50 m thick, blocky intervals of low gamma ray count with isolated peaks of moderate to high gamma. The heterolithic facies (FA6 and FA7) are represented by 10 to 40 m thick intervals that zigzag from low to moderate gamma ray count, locally reaching high gamma ray count, with 5 to 15 m between symmetrical peaks. The base of the package is marked by a sharp decrease in gamma ray count and a change to a blocky or zigzag motif (Figure 19).

Depositional connectivity

The western strata have the highest sand percentage and sand-body connectivity of the Wanneroo Member (Figure 22b). The sand-rich distributary channel-fills and incised valley-fills (FA5) have the highest porosity of the Wanneroo Member. The valley-fill deposits are 30 to 50 m thick and correlate laterally over 5 to 10 km, making them the main high porosity sand bodies of the Leederville aquifer. They are only present in the western section of the Wanneroo Member. The channel-fill sand bodies are 10 to 30 m thick and, although lateral correlation was not possible, are expected to be 10 to 300 m wide (Gibling 2006). The intervening heterolithic tidal flats (FA6 and FA7) are typically composed of silty sand with some sand-rich intervals and have a lower overall porosity.

b) Centre

Geology

The central section of the Wanneroo Member (Kwlw2) is dominated by heterolithic facies deposited on tidal flats (FA6 and FA7, figures 17 and 19) that formed in interdistributary bays on the lower delta plain (e.g. Mangano and Buatois 2004; Ponten & Plink-Bjorklund 2007). There are minor, 10 to 30 m thick intervals of sand-rich facies that were deposited as tidally-influenced channel-fill complexes (FA5) by distributaries migrating across the delta plain (e.g. McIlroy 2004; Ponten & Plink-Bjorklund 2007). These facies associations are present in a narrow, north–south band just east of the centre of the study area (Figure 22a).

Gamma ray motif

The central gamma ray motif is a composite motif made up of two characteristic intervals (figures 19 and 21). The motif is dominated by 10 to 40 m thick intervals that zigzag from low to moderate gamma ray count, locally reaching high gamma ray count, with 5 to 15 m between symmetrical peaks. This pattern represents the heterolithic facies (FA6 and FA7). There are minor, 10 to 30 m thick blocky intervals of low gamma ray count with isolated peaks of moderate to high gamma. This pattern represents the sand-rich facies (FA5). The base of the package is marked by a sharp decrease in gamma ray count and a change to a blocky or zigzag motif (Figure 19).

Depositional connectivity

The central section of the Wanneroo Member is an important part of the Leederville aquifer, but has a lower sand percentage and sand-body connectivity than the western section due to the increased proportion of heterolithic tidal flat deposits. The main high porosity units are the distributary channel-fill sand bodies (FA5), which are 10 to 30 m thick and, although lateral correlation was not possible, are expected to be 10 to 300 m wide (Gibling 2006). The intervening heterolithic tidal flats (FA6 and FA7) are typically composed of silty sand with some sand-rich intervals and have a lower overall porosity.

c) East

Geology

The eastern section of the Wanneroo Member (Kwlw3) is dominated by silt-rich facies, with minor 2 to 4 m thick intervals of sand-rich facies. These facies were deposited during channel avulsion on the upper delta floodplain (FA2, figures 17 and 19) in fluvial, non-marine conditions. There are also rare, 10 to 20 m thick intervals of sand-rich facies that were deposited as channel-fill complexes (FA1, figures 17 and 19) by distributaries migrating across the delta plain. These facies associations are present in a narrow band along the eastern margin of the study area (Figure 22a).

Gamma ray motif

The eastern gamma ray motif is a composite motif made up of two characteristic intervals (figures 19 and 21). The motif is dominated by a zigzag from low to high gamma ray count with 2 to 10 m between symmetrical peaks, dominated by high gamma ray count. There are rare 10 to 20 m thick intervals of low gamma ray count. The base of the package is marked by a sharp decrease in gamma ray count and a change to a zigzag motif (Figure 19).

Depositional connectivity

The eastern strata have the lowest overall sand percentage and sand-body connectivity of the Wanneroo Member (Figure 22b). The dominant, silt-rich floodplain association (FA2) has a low porosity and minor, poorly connected sand bodies. The channel-fill sand bodies (FA1), while they have a high porosity, are rare and poorly connected.

3.6 Pinjar Member

The Pinjar Member (Kwlp) is composed of silt-rich, locally sand-rich facies deposited on a delta front in nearshore to open marine conditions (figures 17 and 19). Lower shoreface to offshore deposits are well developed across most of the study area, with upper shoreface deposits confined to the eastern margin of the basin. The geology and gamma ray motif of the package varies laterally and the study area is divided into three distinct sections: west, centre and east (Figure 23a). The package is typically ~50 to 150 m thick and is present throughout the eastern half of the Gnangara Mound and a small area in the north-west (Figure 23). Within the study area the package corresponds to the *B. jaegeri,* locally *F. monilifera* palynological zones (Figure 19, Barremian to Early Aptian).

a) West

Geology

The western section of the Pinjar Member (Kwlp1) is composed of 10 to 30 m thick, sharp-based intervals of silt-rich facies that coarsen upwards with locally sandy tops. These intervals were deposited as stacked, prograding delta-front bars (FA4, figures 17 and 19) in a low energy, lower shoreface to offshore setting. This facies association is present in the north-west and in a narrow band that runs north–south through the centre of the study area (Figure 23a).

Gamma ray motif

The western gamma ray motif is composed of 10 to 30 m thick, sharp-based, stacked, bell-shaped intervals dominated by high gamma ray count (figures 19 and 21). In each interval gamma ray count decreases upwards to moderate, locally low gamma ray count. Overall, the motif is typically composed of one to three stacked bell-shaped intervals. The base of the package is marked by a sharp change to a very high gamma ray count (Figure 19).

Depositional connectivity

The western Pinjar strata act as an aquitard, as lower shoreface to offshore deposits have poor connectivity of sand layers resulting in very low hydraulic conductivities ('offshore transition zone' of Howell et al. 2008).

b) Centre

Geology

The central section of the Pinjar Member (Kwlp2) is characterised by 8 to 15 m scale intercalation of mud-rich and sand-rich intervals, with strata locally coarsening upward from a sharp, silt-rich base. These facies were deposited in variable energy conditions in a lower shoreface to offshore setting, and are present in a narrow band that run north–south just east of the centre of the study area (Figure 23a).

Gamma ray motif

The central gamma ray motif is characterised by a zigzag from low to very high gamma ray count with 8 to 15 m between peaks (figures 19 and 21). Peaks are typically symmetrical, but are locally sharp based with an upwards decrease in gamma ray count. There are approximately even proportions of high and low gamma ray count, but the motif is locally dominated by high to very high gamma ray count. The base of the package is marked by a sharp change to a very high gamma ray count (Figure 19).

Depositional connectivity

Similarly to the western section, these Pinjar strata act as an aquitard, as lower shoreface to offshore deposits have poor connectivity of sand layers resulting in very low hydraulic conductivities ('offshore transition zone' of Howell et al. 2008).

c) East

Geology

The eastern section of the Pinjar Member (Kwlp3) is characterised by sand-rich facies exhibiting an overall coarsening upwards trend. These facies were deposited on a prograding shoreface (FA3, Figure 17) in increasing energy conditions, and are locally present along the eastern margin of the study area (Figure 23a).

Gamma ray motif

The eastern gamma ray motif is characterised by blocky, low gamma ray count (figures 19 and 21). The gamma ray count decreases upwards overall. The base of the package is marked by a sharp drop in gamma ray count and a change to a blocky motif (Figure 19).

Depositional connectivity

The eastern Pinjar strata act as an aquifer, as they are extensively burrowed, sand-rich and have the highest porosity within the Pinjar Member (Figure 23b).

4 Structural geology

4.1 Introduction

Structural features of the Perth Basin

Perth Basin architecture is dominated by north trending, synthetic and antithetic, planar and listric faults (Mory & Iasky 1996; Song & Cawood 2000; Crostella & Backhouse 2000). Normal faults are intersected by transfer structures that vary in character from north to south (Figure 3). In the northernmost part of the basin (north of 29° S) north trending faults are locally terminated by east trending transfer faults (Song & Cawood 1999) whereas in the rest of the basin they are deflected and deformed by north-west striking transfer zones that exhibit no continuous fault plane (Song et al. 2001).

Offshore seismic data have been interpreted to show that most faults are truncated at the Neocomian unconformity (Song & Cawood 2000). However, some faults do cross-cut the Neocomian unconformity in the offshore Abrolhos and Vlaming sub-basins (Spring & Newell 1993; Song & Cawood 2000; Song et al. 2001). Limited onshore seismic data and poor data quality due to absorption of seismic energy by shallow limestones has limited structural understanding of post-rift Cretaceous strata in the onshore central Perth Basin (Crostella & Backhouse 2000). Variation in thickness of post-rift Cretaceous strata in the onshore central Perth Basin has been interpreted by Allen (1979), Davidson (1995), Davidson & Yu (2006) as folding. In contrast, earlier reports by Commander (1974), Allen (1975) and Playford et al. (1976) and a review by (Crostella & Backhouse 2000) proposed localised faulting of post-rift Cretaceous strata in the onshore central Perth Basin.

Cretaceous fault activity

This report presents a new structural interpretation, incorporating four faults that were active during deposition of the Warnbro Group: the Badaminna, the Darling and the Serpentine faults and the newly recognised Wanneroo Fault (figures 24 and 25). Previous work by Davidson (1995) proposed that fault activity within the study area ceased during the Late Jurassic, and that the variation in thickness of Cretaceous strata was caused by penecontemporaneous subsidence, differential compaction of older strata, and draping over fault blocks. This study acknowledges the influence of subsidence due to sediment compaction, but does not support sediment draping over fault blocks, as Warnbro Group stratal packages dip and thicken towards interpreted faults, indicating syn-depositional fault activity (Leyland 2011). Instead this report proposes a greater influence of Early Cretaceous fault movement in the onshore Perth Basin, as suggested in earlier work by Allen (1975) and Playford et al. (1976) and in a structural review by Crostella & Backhouse (2000).

In the PRAMS model the Cretaceous to Holocene geology is based on a gently folded and draped rather than faulted interpretation (Davidson & Yu 2006). Therefore the new faulted interpretation has implications for aquifer connectivity, both between the Leederville and other aquifers and within the Leederville aquifer between offset fault blocks. This connectivity is discussed below.

Fault zone character

In this study each fault is simplified to a single, vertical, planar structure, based on the steep planar profile of the Darling and Badaminna Faults (Song & Cawood 2000; Crostella & Backhouse 2000). However, movement may be distributed over many smaller faults which accompany the main fault, and movement may be further distributed due to the weakly consolidated strata (Manzocchi et al. 2008). The most distributed fault zone may resemble a fold-like structure. However, it is unlikely that deformed aquiclude strata are completely intact and laterally continuous across the fault zone. Consequently, hydraulic connectivity is expected across the faults between juxtaposed aquifer strata. Due to the poor consolidation of the strata (Leyland 2011), no fault zone factures or fault gouge are expected, and therefore the faults themselves are expected to have a hydraulic permeability similar to that of the offset strata. The hydraulic properties of the fault zone should be carefully considered when constructing a numerical model, and a range of alternative fault zone geometries should be explored.

Periods of erosion

The degree of connection between the Leederville, the Yarragadee and Superficial aquifers is also affected by erosion. There were three main erosion periods: localised erosion prior to Aptian deposition of the Coolyena Group; localised, high relief erosion prior to Paleocene deposition of the Kings Park Formation; widespread erosion prior to Pliocene deposition of the Superficial aquifer. A revised interpretation of the extent of this erosion and the thickness and distribution of strata is presented below.

4.2 North-western study area

Badaminna Fault activity

In the north-western study area there was Early to Late Cretaceous syn-depositional movement along the Badaminna Fault. This generated thick intervals of Warnbro and Coolyena Group strata that dip and thicken to the south-east towards the north trending Badaminna Fault (figures 26 to 31). This report also proposes that local accommodation for the Kings Park Formation was created by Early Eocene syn-depositional movement along the southern segment of the fault (Figure 32).

In reports by Davidson (1995) and Davidson and Yu (2006), the onshore Badaminna Fault was interpreted to have ceased activity during the Late Jurassic. However, Playford et al. (1976) and Crostella & Backhouse (2000) proposed continued activity into the Early Cretaceous.

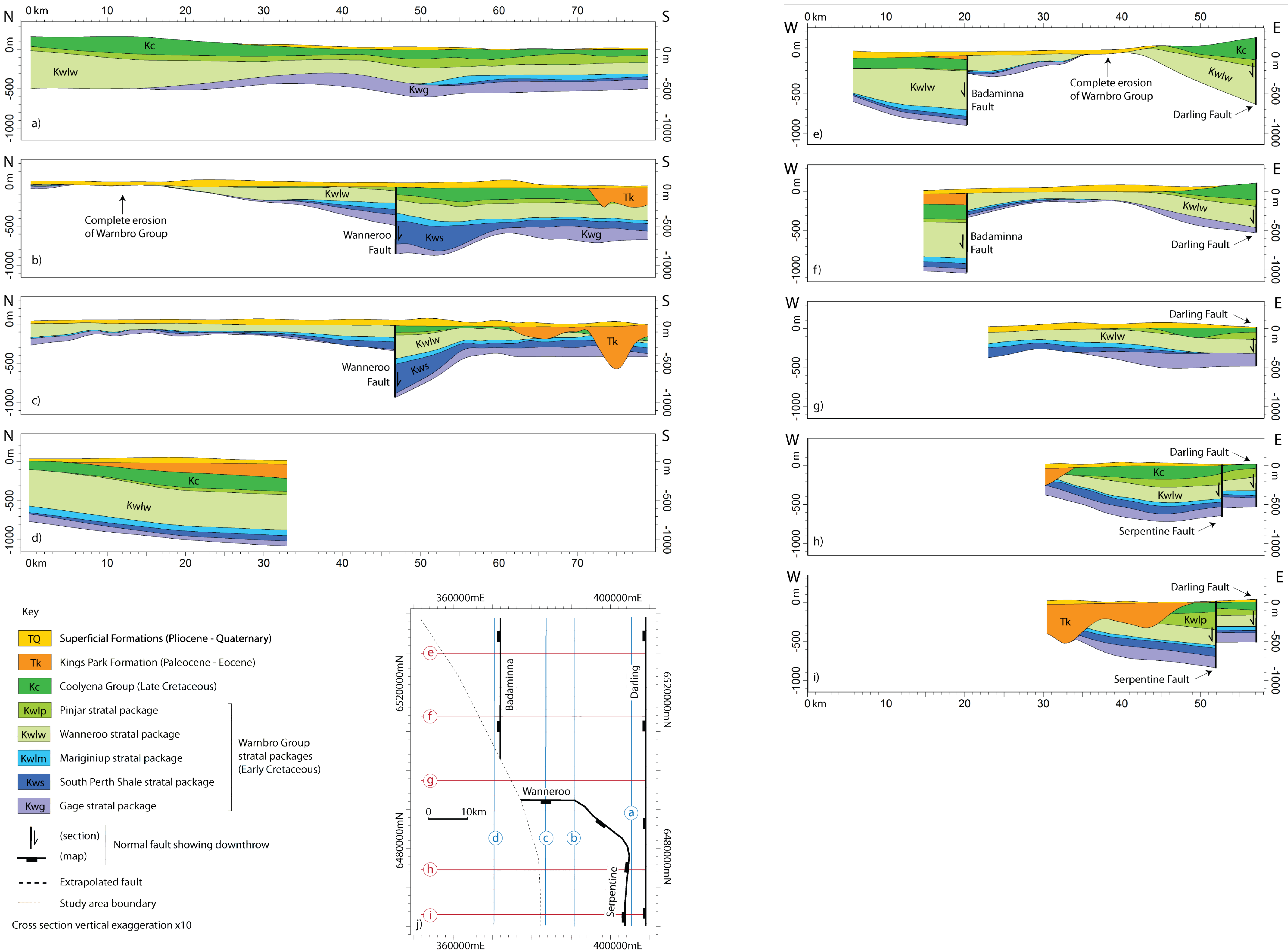


Figure 24 Cross-sections illustrating faults and Lower Cretaceous to Holocene strata of the study area. N-S cross sections (a) to (d) and W-E cross sections (e) to (i). (j) Map view showing faults and section lines.

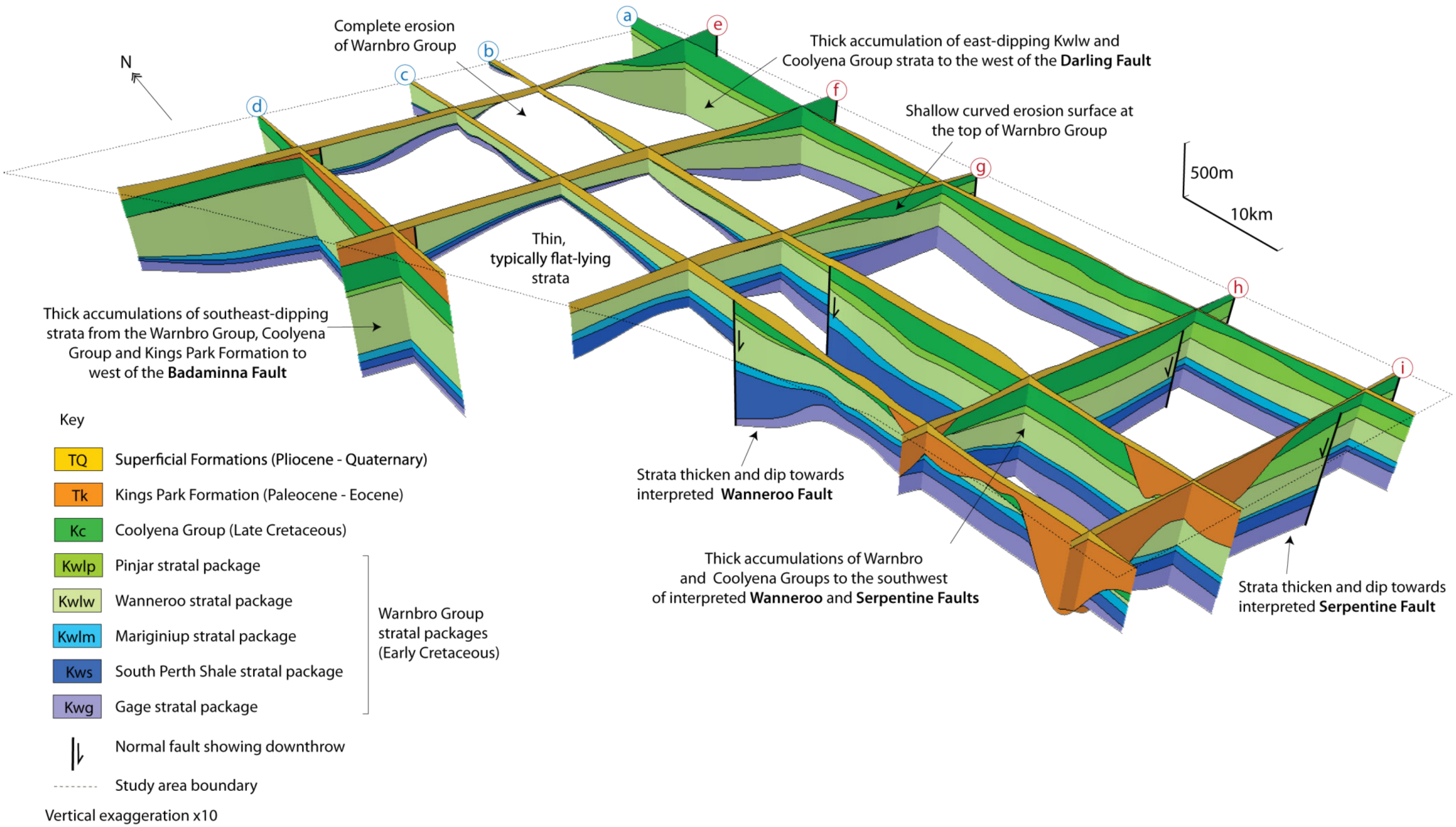


Figure 25 Perspective 3D view of study area from south-west showing faults and Lower Cretaceous to Holocene strata. N–S cross-sections (a) to (d) and W–E cross-sections (e) to (i) from Figure 24.

Aptian erosion

Prior to Late Cretaceous deposition of the Coolyena Group, there was limited erosion of the Pinjar Member (Figure 30). Movement on the southern section of the Badaminna Fault focused erosion in the north-west corner of the study area, where the Pinjar Member is completely eroded.

Aquifer connectivity

To the west of the Badaminna Fault, the Leederville aquifer is separated from the Superficial aquifer by the Coolyena Group, and from the Yarragadee aquifer by the South Perth Shale (Figure 24). In addition, fault offset on the Badaminna Fault has largely disconnected the western and eastern portions of the Wanneroo Member, except where there is some minor connection in along the northernmost segment of the fault. However, fault offset on the Badaminna Fault has connected the Wanneroo Member and the Yarragadee aquifer over a thickness of up to 500 m (Figure 24).

4.3 Northern study area

Darling Fault activity

Movement along the Darling fault varied from north to south. On the northern segment of the fault there was a period of inactivity during the Valanginian to Early Hauterivian. During this time a structural high existed in the north-eastern study area, resulting in a lack of accommodation for sediment deposition. As a result, the Gage, South Perth Shale and Mariginiup Member are absent from the north-eastern study area (figures 26–28). Fault movement on this segment then occurred from the Late Hauterivian to Late Cretaceous. This created accommodation for thick intervals of the Late Hauterivian to Barremian, Wanneroo and Pinjar members and the thickest preserved intervals (200 to 300 m thick) of the Coolyena Group (figures 29 to 31). Due to the syn-depositional fault movement these strata dip and thicken to the east towards the Darling Fault (figures 24 and 25).

Aptian erosion

Prior to the Late Cretaceous deposition of the Coolyena Group, there was limited erosion of the Pinjar Member. This erosion created a shallow valley that ran southwards parallel to the Darling Fault and resulted in the complete erosion of the Pinjar Member in a small area in the central east (Figure 30).

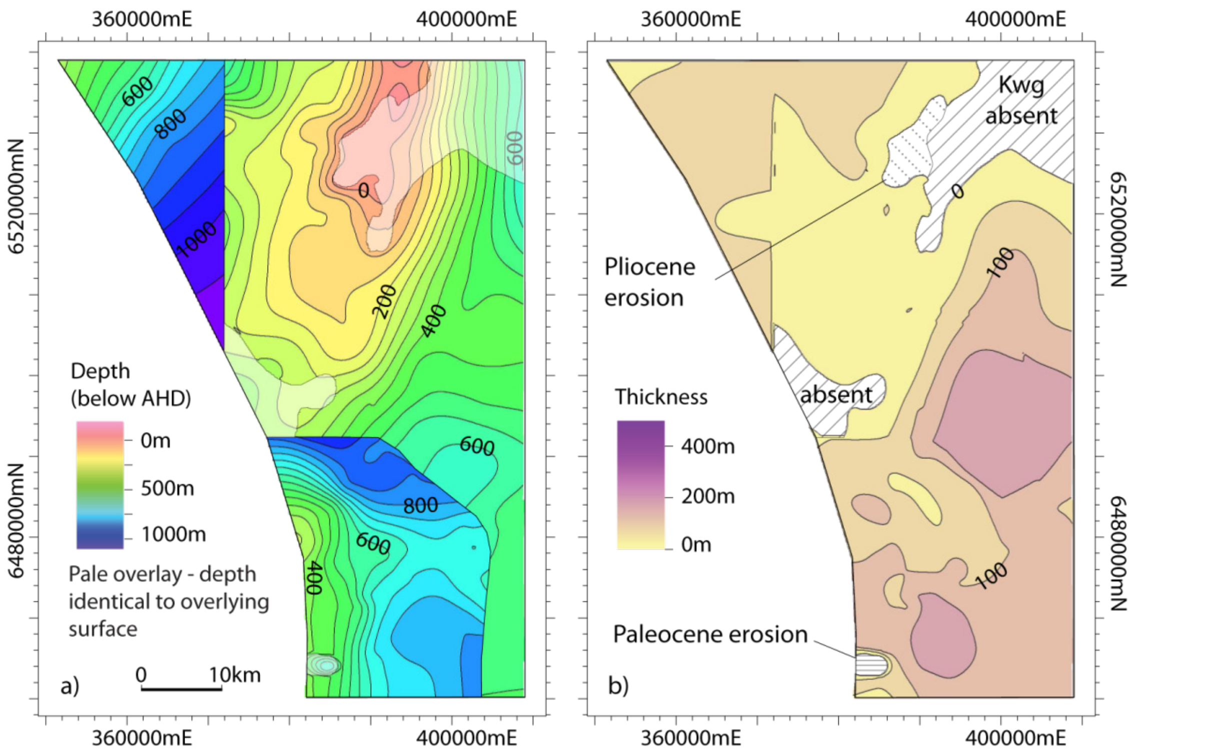


Figure 26 (a) Intra-Valanginian unconformity, depth in metres below AHD, (b) thickness of the overlying Gage Formation in metres. All contours at 50 m intervals.

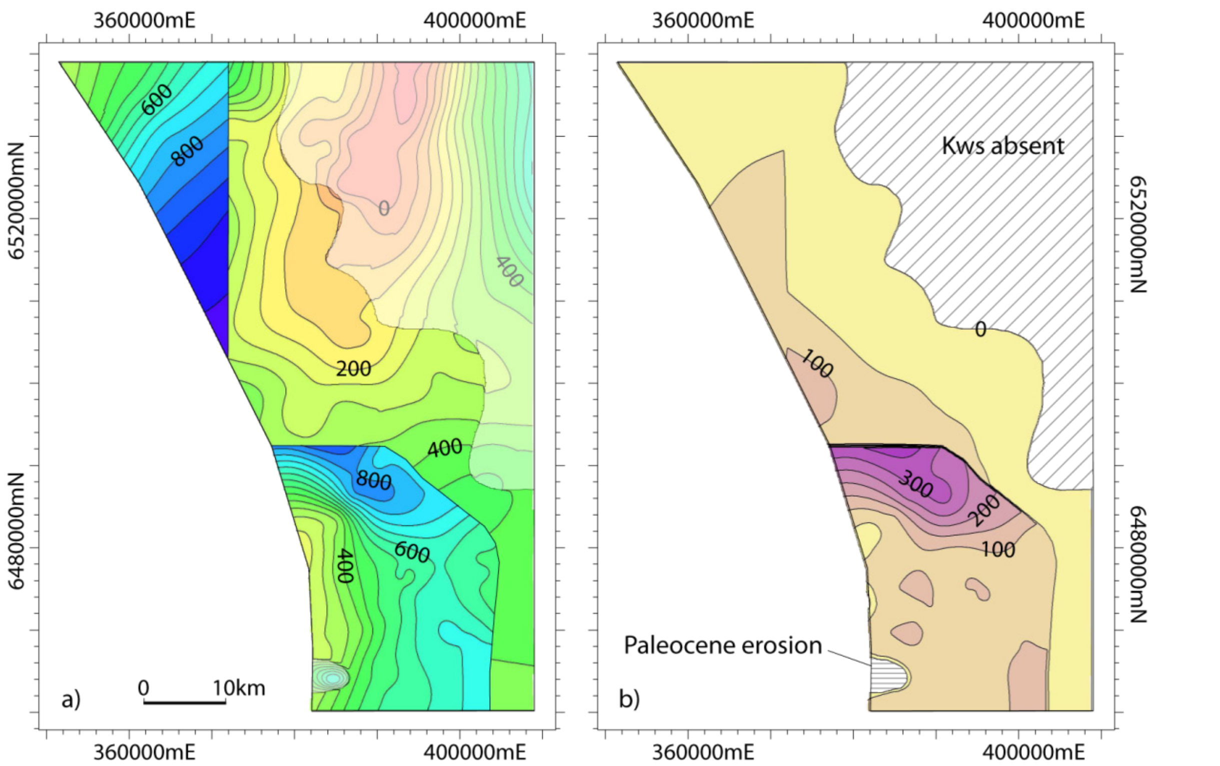


Figure 27 South Perth Shale: (a) depth of base in metres below AHD, (b) thickness in metres. All contours at 50 m intervals, key in Figure 26.

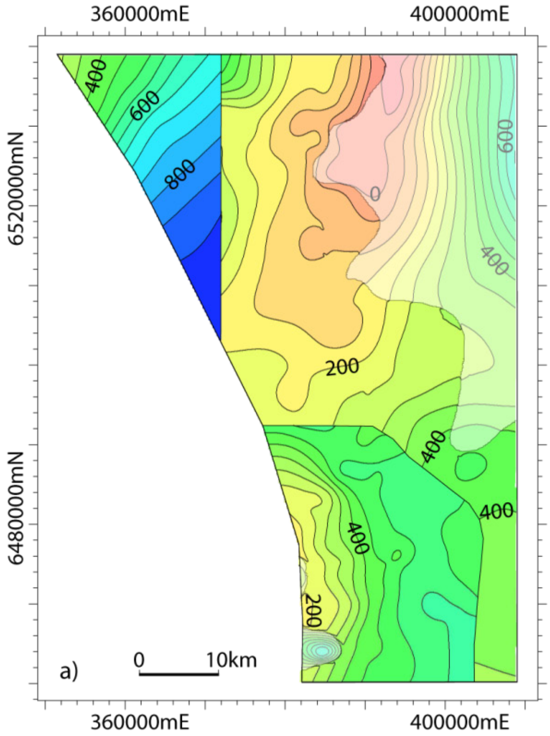


Figure 28 Mariginiup Member: (a) depth of base in metres below AHD, (b) thickness in metres. All contours at 50 m intervals, key in Figure 26.

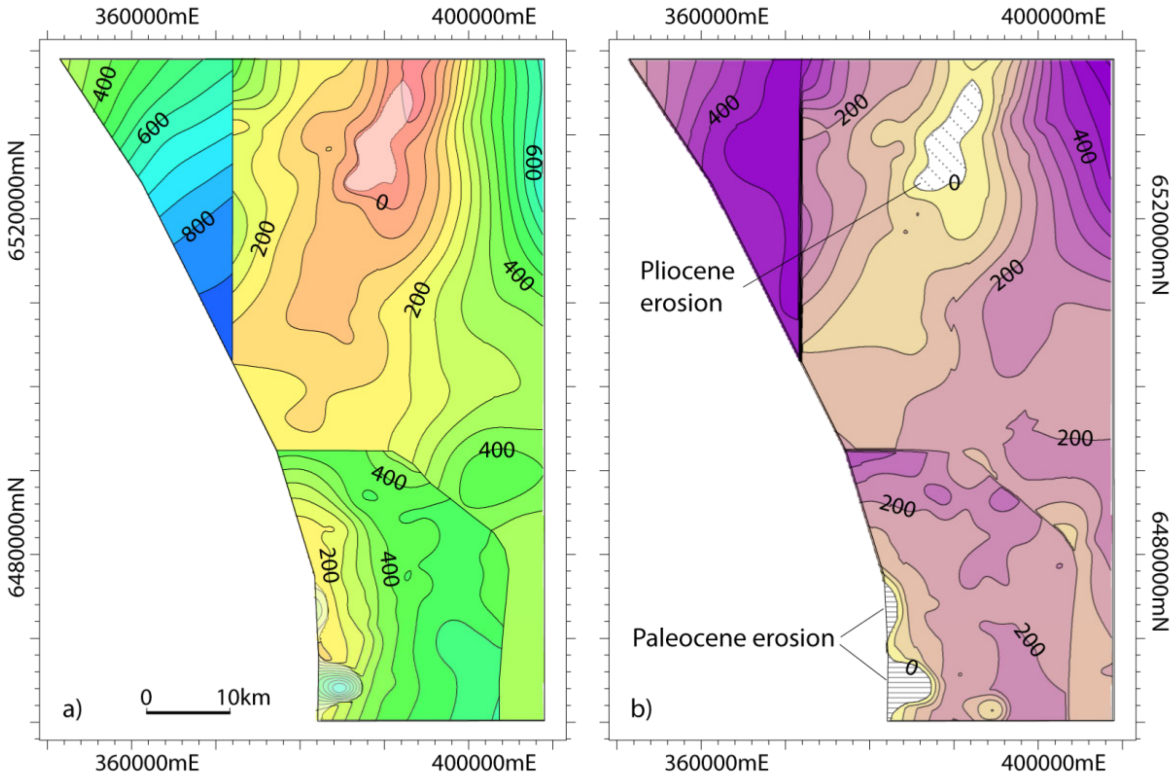


Figure 29 Wanneroo Member: (a) depth of base in metres below AHD, (b) thickness in metres. All contours at 50 m intervals, key in Figure 26.

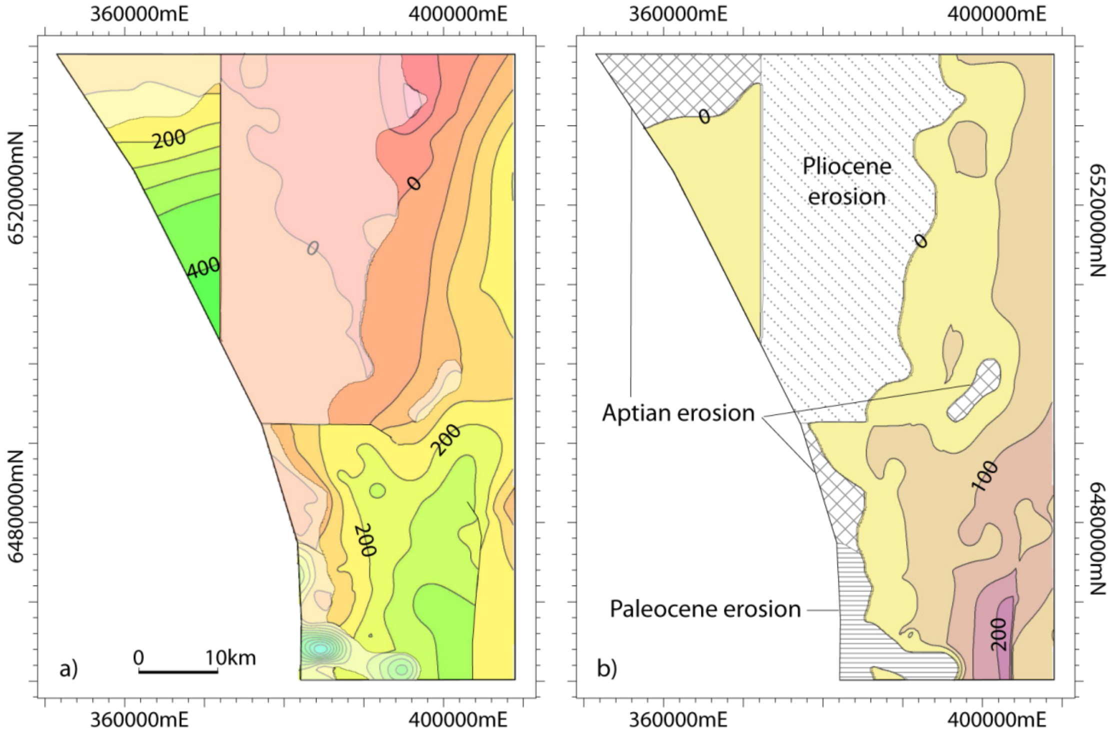


Figure 30 Pinjar Member: (a) depth of base in metres below AHD, (b) thickness in metres. All contours at 50 m intervals, key in Figure 26.

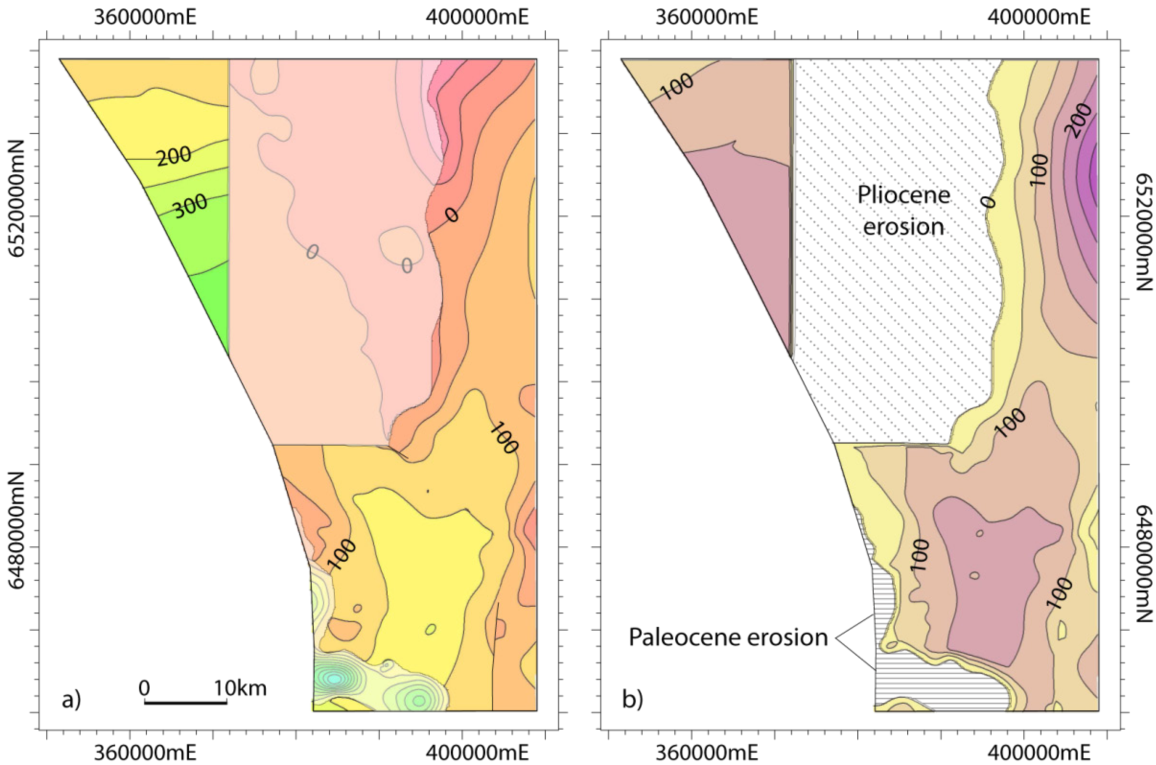


Figure 31 (a) Intra-Aptian unconformity, depth in metres below AHD, (b) thickness of the overlying Coolyena Group in metres. All contours at 50 m interval, key in Figure 26.

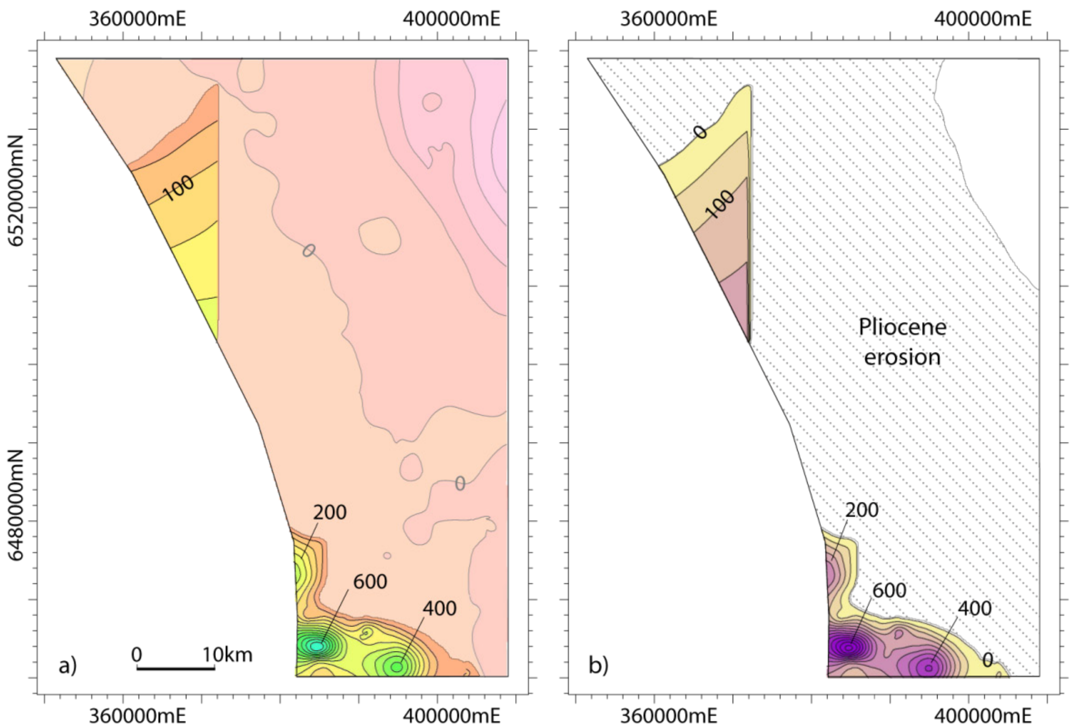


Figure 32 (a) Paleocene unconformity, depth in metres below AHD, (b) thickness of the overlying Kings Park Formation in metres. All contours at 50 m intervals, key in Figure 26.

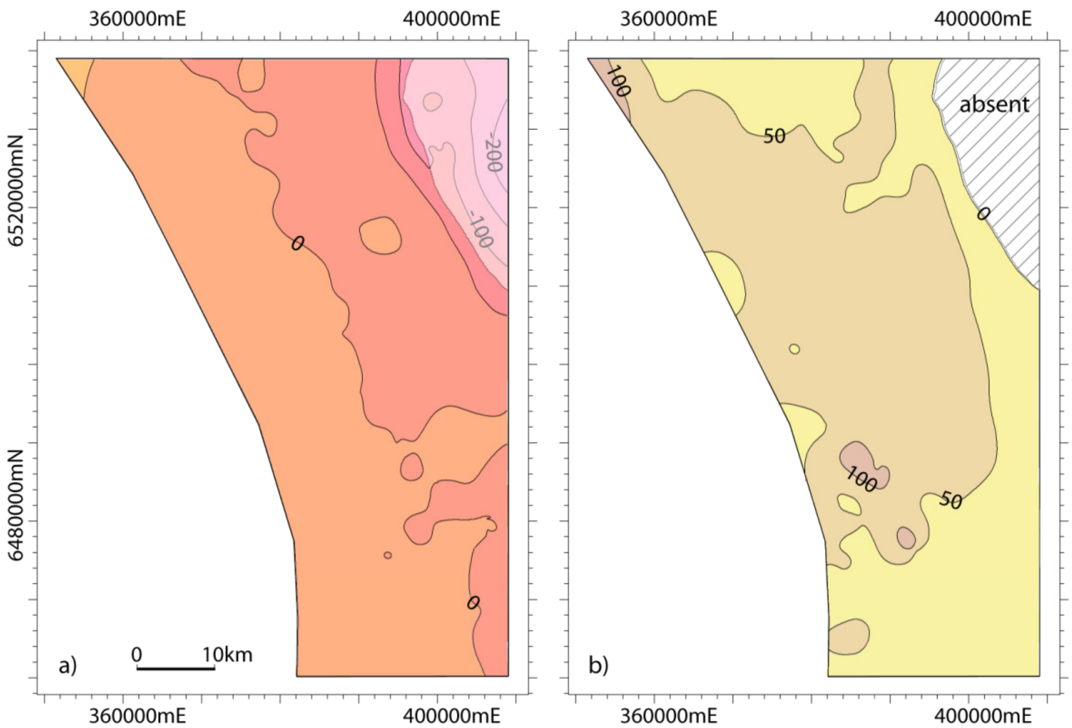


Figure 33 (a) Pliocene unconformity, depth in metres below AHD, (b) thickness of the overlying superficial formations in metres. All contours at 50 m intervals, key in Figure 26.

Pliocene erosion

Prior to the Pliocene deposition of the Superficial aquifer, there was widespread erosion of the Coolyena Group and the Pinjar and Wanneroo members. Movement on the Badaminna and Darling faults focused uplift and erosion to the east of the Badaminna Fault and north of the Wanneroo Fault. As a result, the Coolyena Group and the Pinjar Member were completely eroded across the centre of the study area, and the Wanneroo Member was also completely eroded in a small area in the central north (figures 29 to 31). There was also partial erosion of the Pinjar Member and the Coolyena Group across the rest of the mound (figures 29 to 31).

Aquifer connectivity

Across the centre of the study area, where both the Coolyena Group and the Pinjar Member have been completely eroded, the Wanneroo Member is in direct contact with the Superficial aquifer (figures 30 and 31). Along the coast in the central west, just north of the Wanneroo Fault, a ~50 m thick interval of Superficial aquifer connects the Wanneroo Member to the ocean.

Along the eastern margin of the window in the Coolyena Group, thin (<50 m thick) intervals of silt-rich Pinjar Member lie between the Wanneroo Member and the Superficial aquifer (Figure 30). Further east, fault offset of the Darling Fault has downthrown the Coolyena Group aquiclude against the Yilgarn Craton, and the Leederville aquifer is confined (Figure 31).

The Leederville aquifer is separated from the Yarragadee aquifer across the south-west of the area by the South Perth Shale (Figure 27). In the north-east, where both the Mariginiup Member and South Perth Shale are absent, the Wanneroo Member is in direct contact with the Yarragadee or Parmelia aquifers.

4.4 Southern study area

Wanneroo, Serpentine and Darling Fault activity

During the Early to Late Cretaceous there was fault movement along the Wanneroo, Serpentine and Darling faults (figures 24 and 25). The Wanneroo Fault does not correspond to any previously recognised structure. However, earlier interpretations by Allen (1975) and Backhouse (1988) proposed a north-east trending fault that offset the Warnbro Group in a similar location. The Serpentine Fault was previously mapped to the south by Davidson and Yu (2006), and is interpreted in this study to extend north into the study area. The regional structural style would suggest that outside the study area the Wanneroo Fault trends north towards the Badaminna Fault (Song & Cawood 2000).

Fault activity on the Wanneroo and Serpentine Faults created accommodation for thick intervals of Warnbro Group and Coolyena Group strata in the south-west study area (figures 26 to 31). Due to the syn-depositional fault movement, these strata dip and thicken to the east and north towards the north trending Serpentine and east trending Wanneroo Faults (figures 24 and 25). Along the southern segment of the

Darling fault there was steady movement from Early to Late Cretaceous. This created accommodation for largely flat-lying, locally tilted, Warnbro and Coolyena Group strata in the south-east study area.

Aptian erosion

Prior to the Late Cretaceous deposition of the Coolyena Group, there was limited erosion of the Pinjar Member. Movement on the Wanneroo, Serpentine and Darling faults focused erosion in the western margin of the study area, where the Pinjar Member is completely eroded (Figure 30). In addition, there was minor erosion of the Pinjar Member in a wide shallow valley that ran southwards to the west of the Serpentine Fault.

Paleocene erosion

Prior to the Paleocene deposition of the Kings Park Formation, there was significant, high relief (up to 600 m), erosion of an incised river valley or submarine canyon (Playford et al. 1976). Erosion was focused in the south-west of the study area and the Kings Park Formation is restricted to this area (Figure 32). Within the Kings Park Formation there are two sand-rich intervals, the Como and the Mullaloo Sandstone members (Davidson 1995).

Aquifer connectivity

The Leederville aquifer is confined by the Coolyena Group across most of the south Gnangara groundwater system (Figure 31). In the south-western corner of the mound, where the Coolyena Group is absent, the Leederville aquifer is bounded to the west by the Kings Park Formation (Figure 24) and there may be some connectivity with the minor sand-rich Como and Mullaloo Sandstone members.

Along the Wanneroo Fault and the northern segment of the Serpentine Fault, there is some connectivity between the offset portions of the Wanneroo Member (Figure 24). Along the southern segment of the Serpentine Fault, the offset portions of the Wanneroo Member are disconnected.

The Leederville aquifer is separated from the Yarragadee aquifer across most of the southern study area by the South Perth Shale (Figure 27). There is locally some connection between the Wanneroo Member and the Yarragadee aquifer along the western segment of the Wanneroo Fault and the southern section of the Serpentine Fault (Figure 24) .

5 Hydrogeology

5.1 Introduction

This chapter presents a 3D hydrogeological model of the Leederville aquifer within the Gnangara groundwater system. The conceptual flow model is based on the groundwater salinity distribution, the September 1987 hydraulic head distribution, groundwater age data and the aquifer connectivity.

The groundwater salinity distribution presented is this study was based on a formation resistivity factor of 4.9 and a matrix resistivity of 200 Ωm. These values were calculated by linear regression from downhole resistivity logs and groundwater conductivity values from thirty AM bores, and are valid for the Wanneroo Member.

The hydraulic heads were collected early in the pumping history of the Gnangara groundwater system and reflect as closely as possible the undisturbed, pre-pumping head distribution, but are locally affected by abstraction in the south-western study area. Although the importance of density driven flow is acknowledged (Simmons 2005), for the Leederville aquifer the maximum equivalent head variation due to salinity is <0.5 m and therefore hydraulic heads are not converted to equivalent fresh water heads.

The groundwater ages used in this study are uncorrected radiocarbon ages interpreted by Thorpe & Davidson (1991). As the Leederville aquifer has a low carbon content with typically <1% carbonate (Descourvieres et al. 2011), carbonate dissolution is therefore minimal and the apparent, uncorrected ages are assumed to be close to the true groundwater age.

5.2 Recharge

Window in the Coolyena Group

The Coolyena Group is absent across the central northern portion of the Gnangara groundwater system (Figure 34). Across most of this window the Pinjar Member is also absent, and major, well connected sand bodies in the Wanneroo Member are in direct connection with the overlying Superficial aquifer. Along the eastern margin of the recharge zone, thin (<50 m) intervals of the Pinjar Member are present, composed of lower shoreface to offshore facies (figures 23 and 34). These facies typically act as an aquitard due to the high silt content and poor connectivity of sand layers (discussed in Section 3.6).

Across central and eastern portions of the window there is a downwards head gradient from the Superficial to the Leederville aquifer. Within this recharge zone, there is vertical percolation of groundwater from the Superficial aquifer which results in fresh young groundwater (4 to 6 kyr old, salinity <250 mg/L) at shallow depths in the Leederville aquifer (Figure 34).

The Pinjar Member is locally overlain by the Henley Sandstone, which is mapped in this study as part of the Coolyena Group (Figure 4), but is defined by Davidson (1995) as part of the Leederville aquifer. In areas where the Pinjar aquitard facies are well developed the Wanneroo Member may be hydraulically isolated from the overlying Henley Sandstone.

Thin Leederville aquifer in the north-east

In the north-east of the recharge zone, the Leederville aquifer is thin (<50 m) or absent, and is composed of minor, poorly connected sand bodies in the Wanneroo Member (figures 22 and 29). Where the Leederville aquifer is absent the underlying Yarragadee aquifer is in direct connection with the Superficial aquifer. The hydrogeology of this area is discussed in detail in Pigois (2012).

Recharge throughout recent glacial and interglacial periods

The Leederville recharge described in this section would have occurred during the present interglacial period. The presence of 15 to 38 kyr old, fresh groundwater in the underlying Yarragadee aquifer (Thorpe & Davidson 1991) suggests freshwater recharge of the Gnangara groundwater system also occurred during the last glacial period.

5.3 Groundwater flow

The overall hydraulic gradient in the Leederville aquifer across the Gnangara groundwater system is north-east to south-west. This flow is driven by the high potentiometric head in the Leederville aquifer below the topographic high of the Dandaragan plateau in the north-east of the study area. The conceptual flow model is represented by seven flow zones (Figure 35).

Local recharge superimposed on regional flow

Fresh, young groundwater recharge (<500 mg/L, 4 to 5 kyr) is superimposed on regional, marginal to brackish groundwater flow (salinity >500 mg/L). This results in a stratified water column, with older, more saline groundwater beneath and to the west and east of the recharge zone (Figure 36). The apparent age of marginal to brackish groundwater increases along the flow path (10 to 30 kyr,), due either to increased residence time or varying degrees of mixing with fresh young water (Glynn & Plummer 2005).

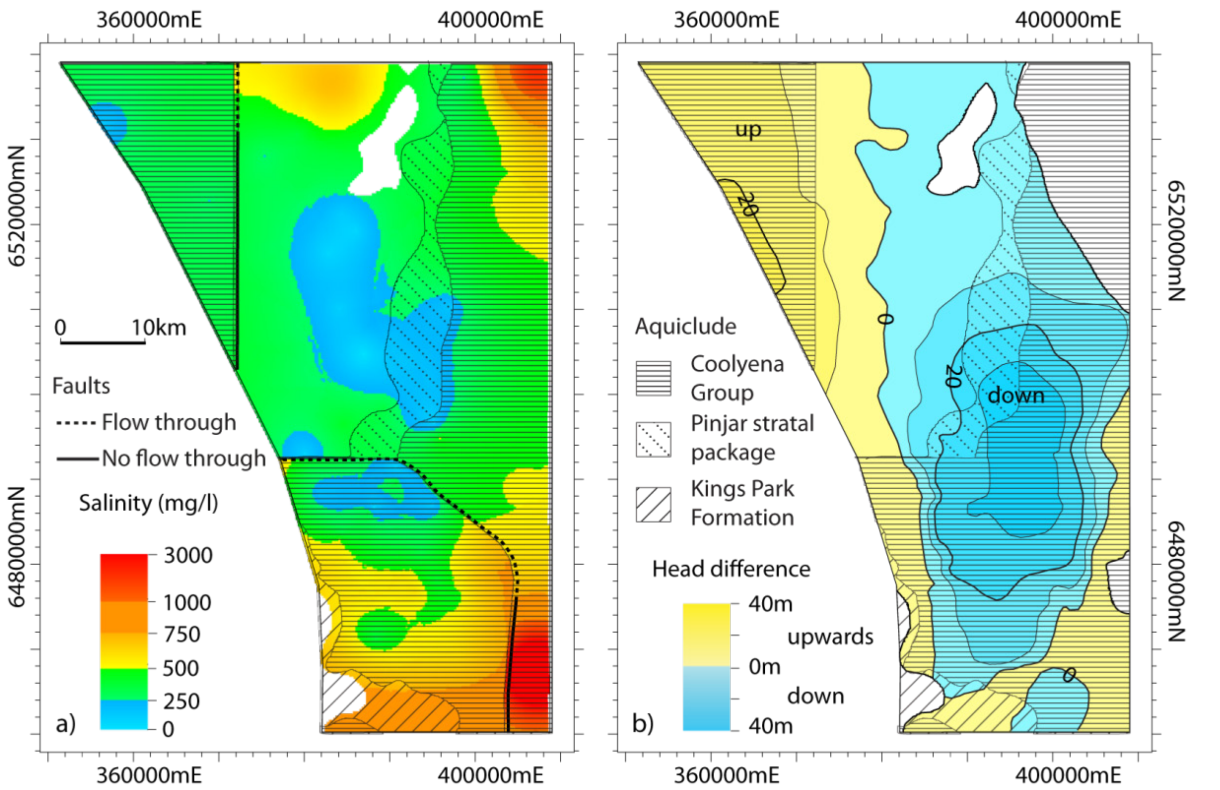


Figure 34 Groundwater salinity distribution and recharge pattern of the Leederville aquifer, showing distribution of aquiclude strata. (a) Salinity distribution at the top of the Leederville aquifer. (b) Head difference between Leederville and Superficial aquifers, 10 m isopotentials.

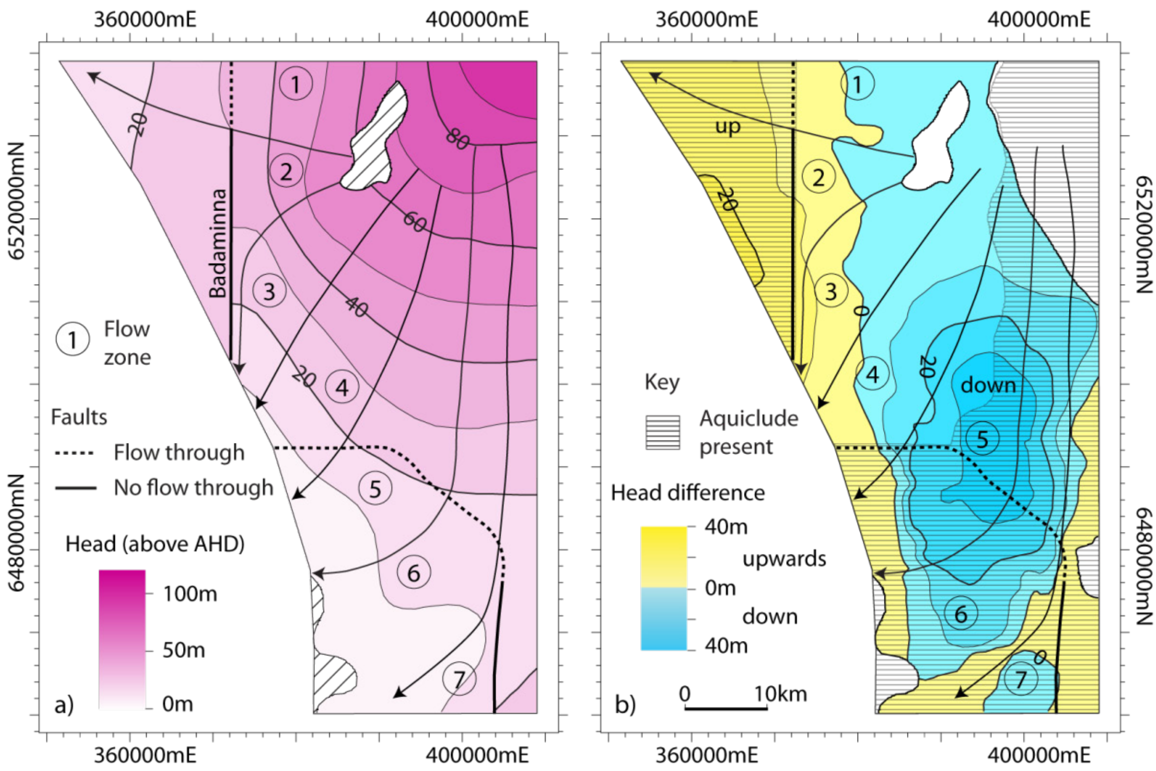


Figure 35 Leederville aquifer flow zones with (a) hydraulic head distribution in metres above AHD and (b) head difference between Leederville and Superficial aquifers, 10 m isopotentials, showing distribution of the Coolyena Group aquiclude.

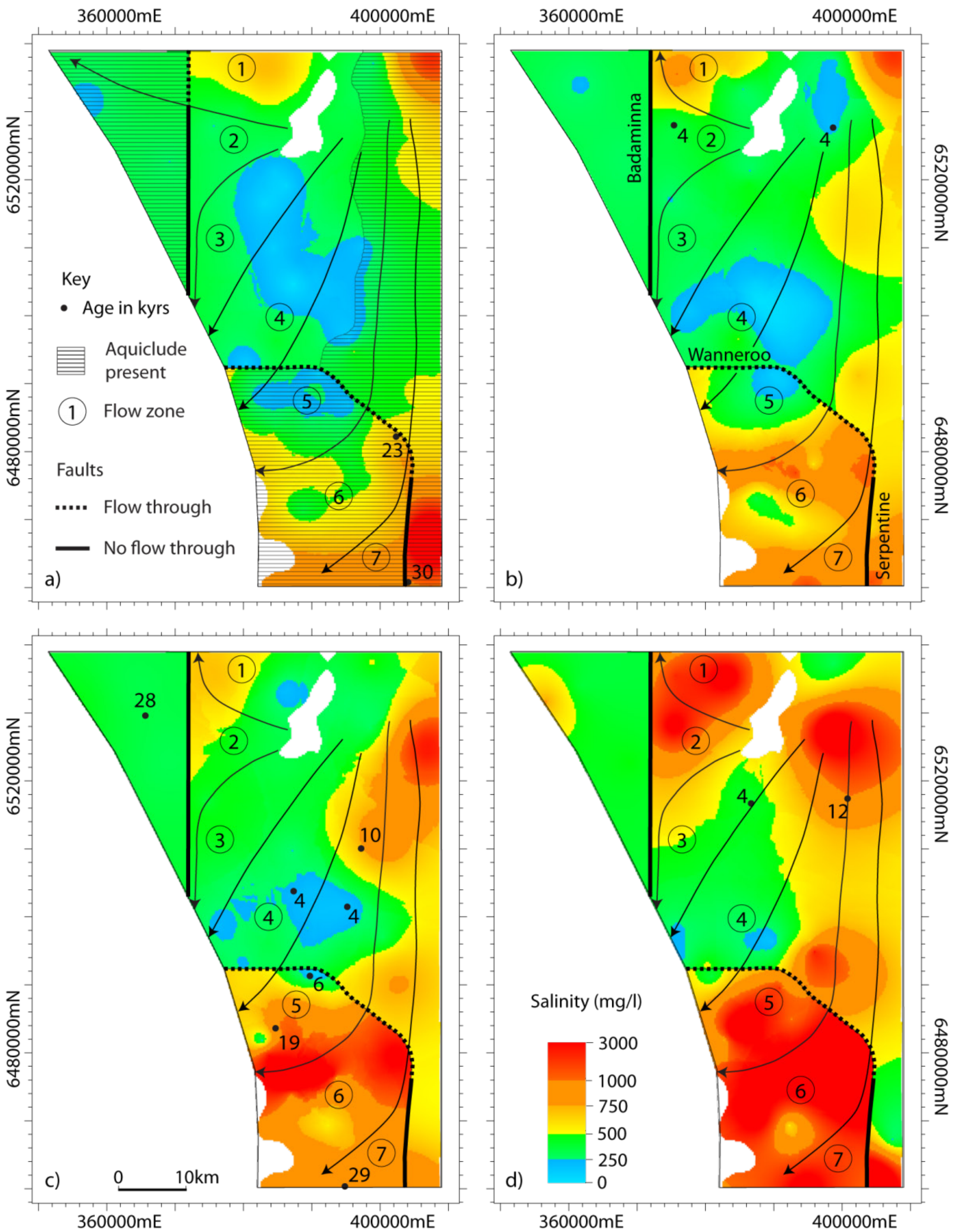


Figure 36 Salinity distribution, groundwater age and flow zones of the Leederville aquifer, in successive stratal horizons from top to bottom. (a) Top, with Coolyena Group aquiclude, (b) upper middle, (c) lower middle, (d) bottom. Uncorrected ages from Thorpe & Davidson (1991), rounded to the nearest kyr.

Flow across the northern Gnangara groundwater system

In the recharge zone a north-east to south-west hydraulic gradient drives groundwater flow (flow zones 3 to 5, Figure 35). Fresh young groundwater (<500 mg/L, 4–6 kyr) flows across the central study area at shallow depths and as recharge from the Superficial aquifer accumulates, the interval of fresh, young groundwater deepens and thickens along the flow path (Figure 36). This fresh recharge is hosted by the heterolithic tidal flat deposits, distributary channel fills and incised valley fills of the Wanneroo Member, with high sand content and well connected sand bodies (flow zones 3 to 5, Figure 37).

To the east of the recharge zone, there is a north to south hydraulic gradient and regional, brackish flow from the north is directed southwards, parallel to the Darling Fault (flow zones 6 to 7, Figure 35). There is little freshwater influence from the Superficial aquifer and marginal to brackish, old groundwater (>500 mg/L, 10–30 kyr) flows southwards at the base of zones 6 and 7 (Figure 36). The aquifer strata hosting this flow are dominated by fluvial floodplain and tidal flat facies of the Wanneroo Member with rare channel-fill deposits, and with moderate sand content and poorly connected sand bodies (Figure 37).

Southward flow across the Wanneroo Fault

To the south of the recharge zone lies the west trending Wanneroo Fault, across which there is ~200 m offset of the Leederville aquifer. There remains some connection between the offset portions of the Leederville aquifer. The hydraulic gradient slopes to the south-west, driving fresh recharge across the fault and creating an area of fresh, young groundwater directly south of the fault (flow zone 5, figures 38 to 40).

In addition, along the western segment of the Wanneroo Fault, there is some connection between the Leederville and Yarragadee aquifers. The upwards hydraulic gradient from the Yarragadee to the Leederville aquifer is expected to drive groundwater south across the fault to recharge the Leederville aquifer (flow zone 4, figures 38 and 39).

Westward flow across the southern Gnangara groundwater system

In the south of the Gnangara groundwater system, flow paths bend west to follow the shallow westward dip of the hydraulic gradient (Figure 35). Fresh groundwater flows westwards (flow zone 5) and the southern study area is fed predominantly by marginal to brackish, regional flow (flow zones 6 and 7, Figure 36). As a result, groundwater in the Leederville aquifer across the southern Gnangara groundwater system is typically marginal to brackish, even at shallow depths.

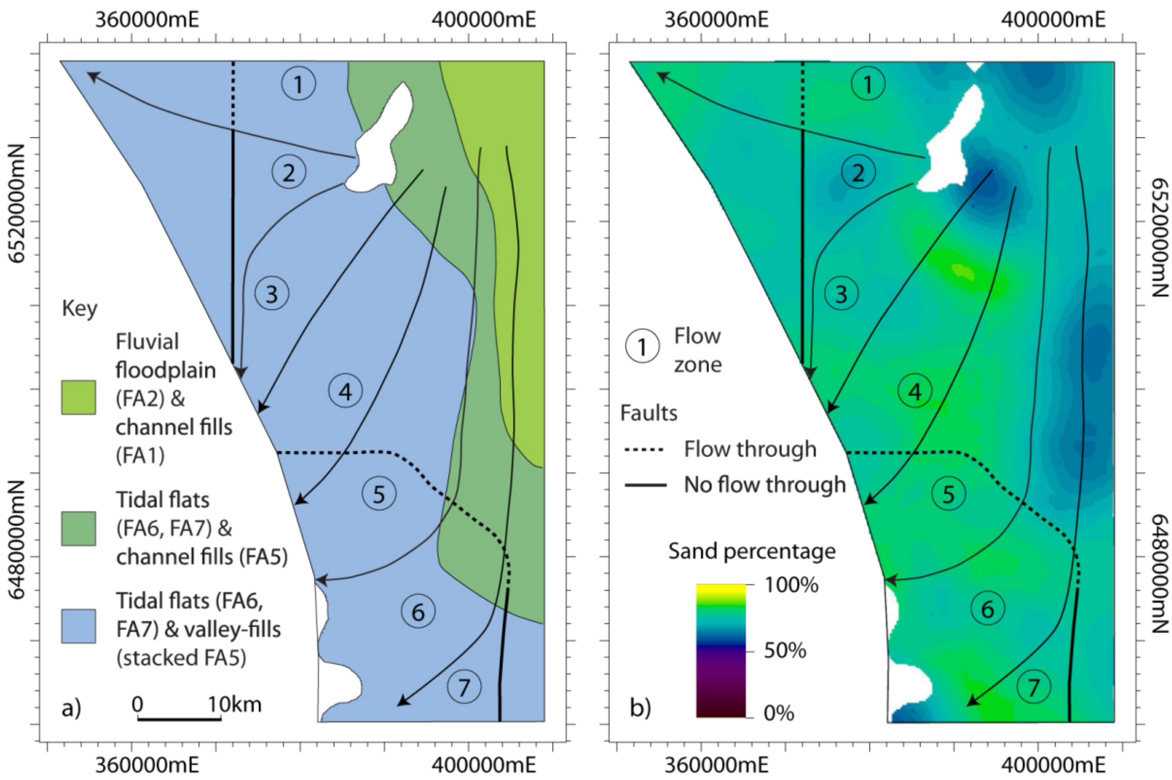


Figure 37 Leederville aquifer interpreted flow zones with (a) facies architecture and (b) sand percentage of the Wanneroo Member.

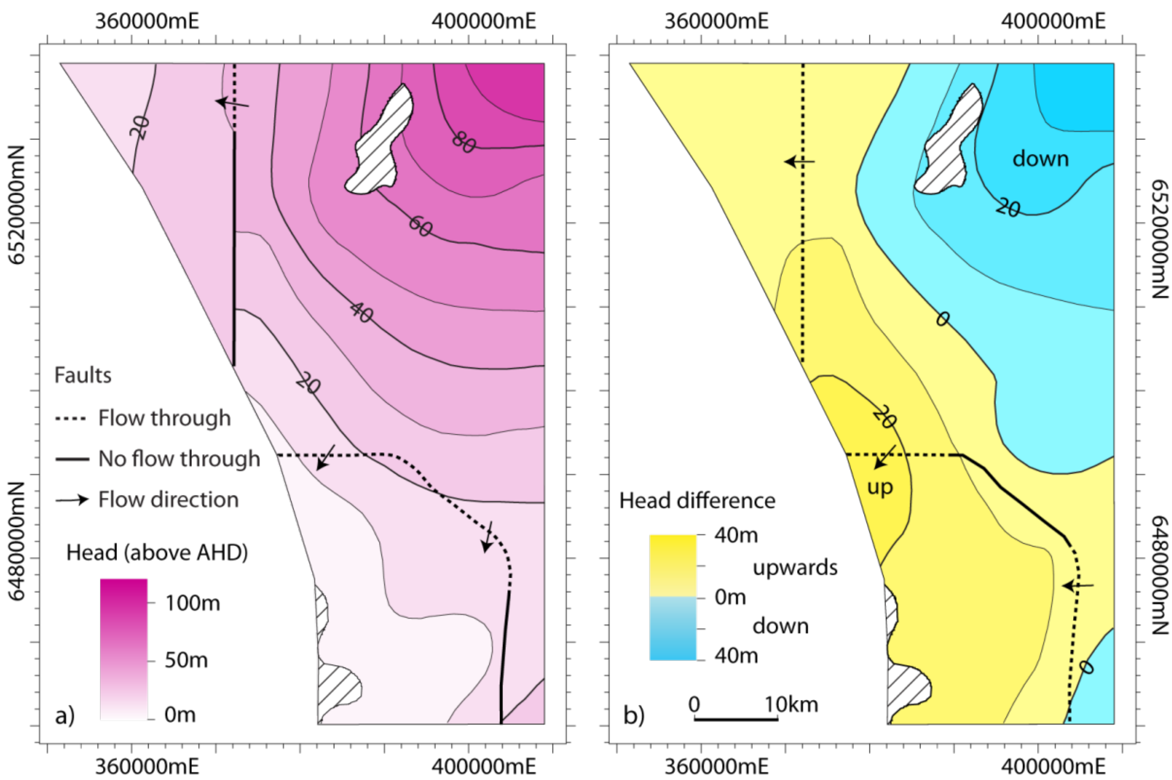


Figure 38 Maps showing south-westward flow across faults. (a) Head gradients and flow within Leederville aquifer. (b) Head difference and flow from the Yarragadee to the Leederville aquifer.

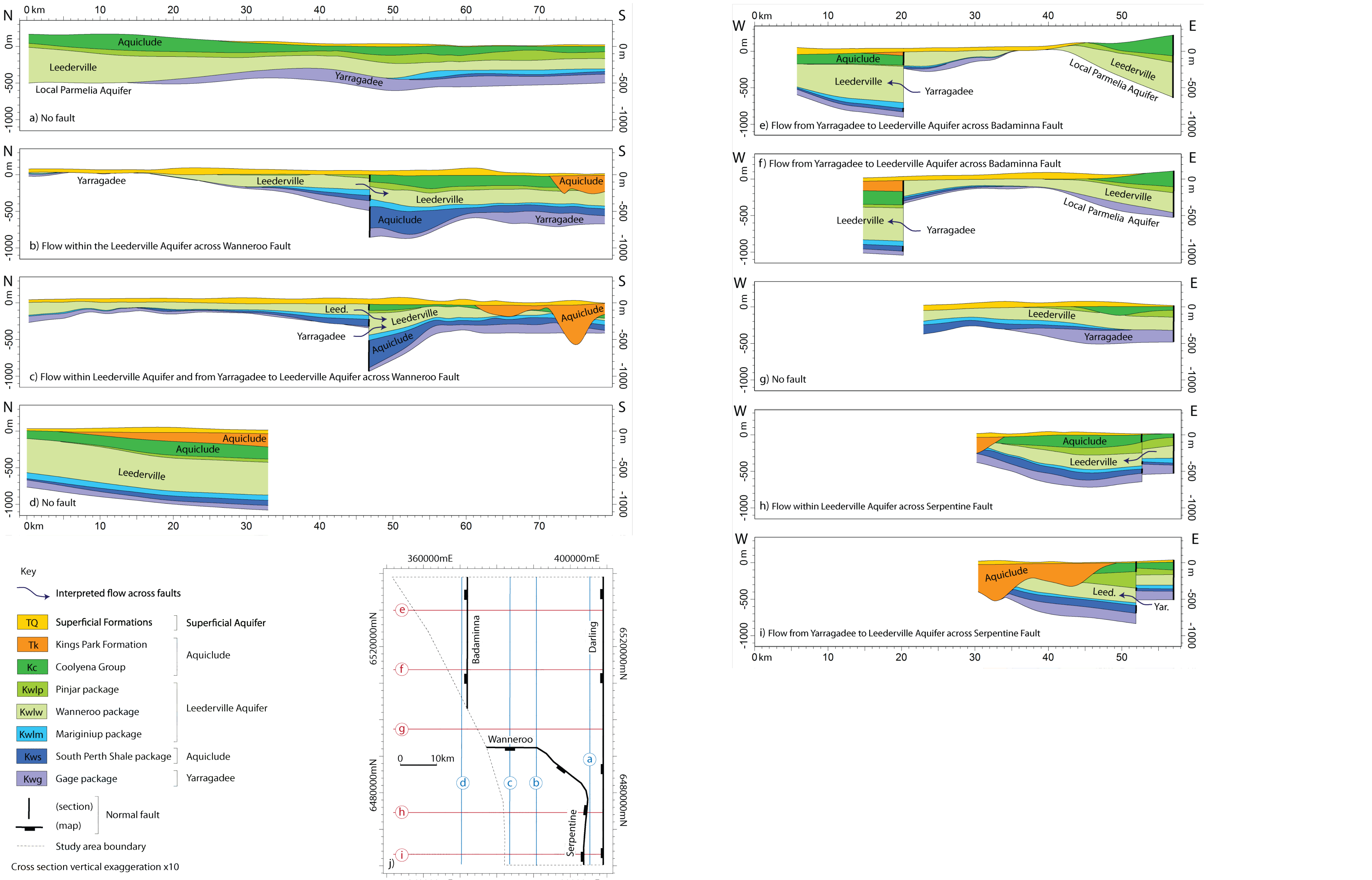


Figure 39 Cross-sections illustrating fault juxtaposition of aquifers, connectivity and flow. N–S cross-sections (a) to (d) and W–E cross-sections (e) to (i). (j) Map view showing faults and section lines. Flow direction interpreted from hydraulic gradients in Figure 38. Note: some flow directions are oblique to faults.

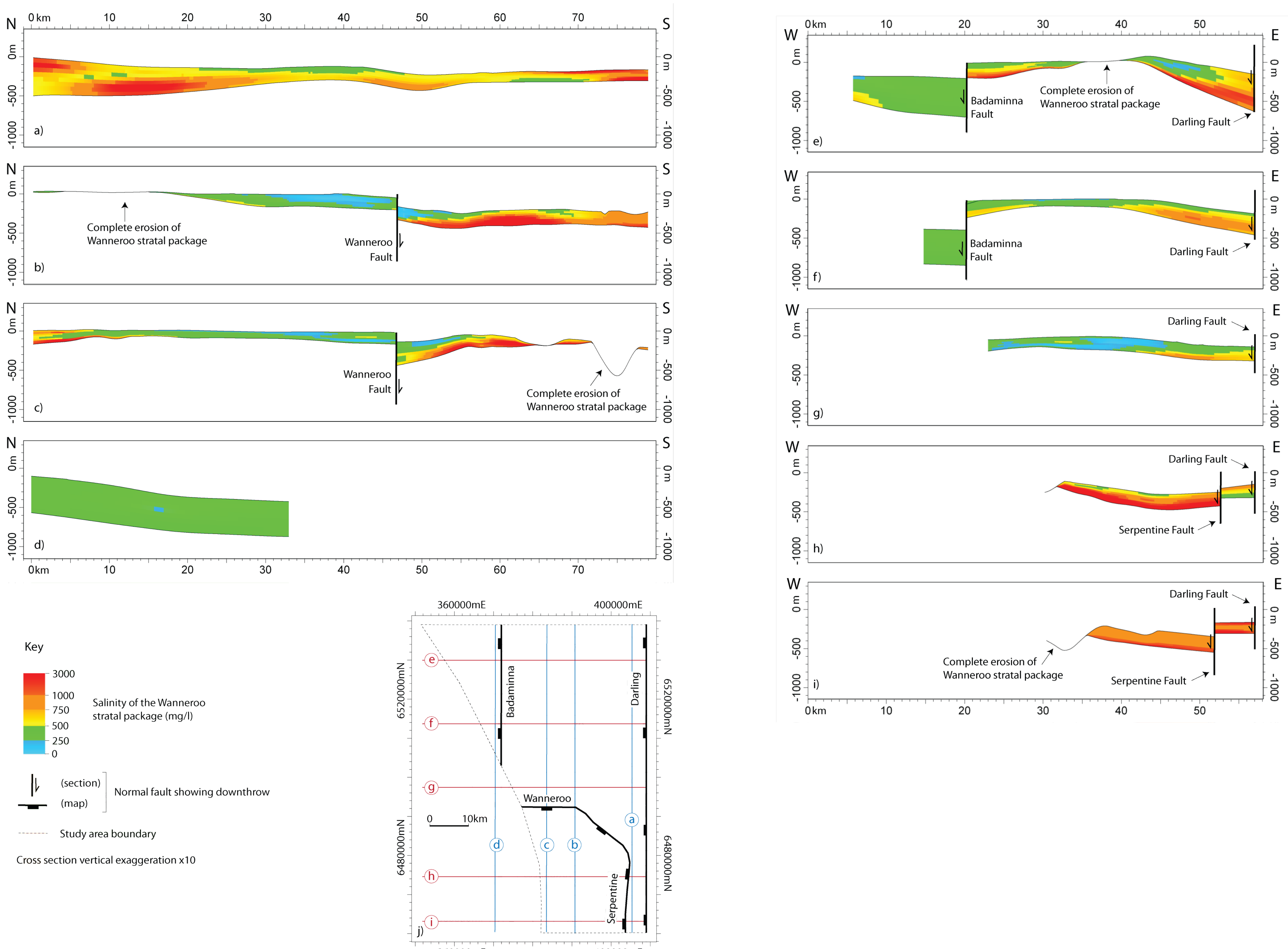


Figure 40 Cross-sections illustrating groundwater salinity distribution in the Leederville aquifer with fault offset. N–S cross-sections (a) to (d) and W–E cross-sections (e) to (i). (j) Map view showing faults and section lines. Fresh groundwater (<500 mg/L) crosses the Wanneroo Fault, and the salinity distribution is less stratified to the west of the Badaminna Fault.

Westward flow across the Serpentine Fault

In the south-east of the Gnangara groundwater system lies the north trending Serpentine Fault, across which there is ~150 m offset of the Leederville aquifer. Along the northern segment of the fault there is some connectivity between the offset portions of the Leederville aquifer (flow zone 6, figures 35 and 39). The north-east to south-west hydraulic gradient is expected to drive groundwater flow south-west across the fault within the Leederville aquifer (Figure 38). Along the southern segment of the fault, the offset portions of the Leederville aquifer are disconnected, and there is some connectivity between the Leederville and Yarragadee aquifers (flow zone 7, figures 35 and 39). Upward head gradients from the Yarragadee to the Leederville aquifer are expected to drive groundwater west across the fault to recharge the Leederville aquifer (figures 38 and 39).

Flow in the region of the Badaminna Fault

In the north-west of the Gnangara groundwater system lies the north trending Badaminna Fault, across which there is ~500 m offset of the Leederville aquifer. The west and east portions of the Leederville aquifer are almost entirely disconnected and groundwater flows south along the fault, or discharges up into the Superficial aquifer (flow zone 2, figures 35 and 39). There is some minor connection along the northernmost segment of the fault (flow zone 1, figures 35 and 39). This hydraulic isolation has resulted in contrasting salinity distributions in the Leederville aquifer either side of the fault (figures 36 and 40). To the west there is old, fresh, unstratified groundwater (28 kyr, salinity <500 mg/L). To the east there is a stratified salinity distribution with young, fresh groundwater (4 to 6 kyr, salinity <500 mg/L) overlying old, marginal to brackish groundwater (10 to 30 kyr, salinity >500 mg/L).

In addition, fault offset has connected the Leederville and the Yarragadee aquifers over a thickness of up to 500 m. The gentle upwards hydraulic gradient from the Yarragadee to the Leederville aquifer is expected to drive groundwater west across the fault, recharging the Leederville aquifer (figures 38 and 39). This explains the exceptional age (28 kyr) of the fresh groundwater in the Leederville aquifer to the west of the fault (Figure 36). This old fresh groundwater is expected to be influenced by the fresh groundwater from the Yarragadee aquifer, which ranges in age from 2 to 38 kyr (Thorpe & Davidson 1991).

5.4 Discharge

In the north-west of the Gnangara groundwater system, along the western margin of the window in the Coolyena Group, upwards head gradients promote discharge into the Superficial aquifer (flow zones 2 to 4, Figure 41a). This discharge is especially significant to the east of the Badaminna Fault where aquicludes in the Coolyena Group and Kings Park Formation that have been downthrown (flow zones 2 and 3, Figure 41a). Along the coast in the central west, in the south-western corner of the window in the Coolyena Group, fresh groundwater discharges up through the Superficial aquifer into the sea. This groundwater discharge is hosted by heterolithic tidal flat deposits, distributary channel fills and incised valley fills of the Wanneroo Member, with high sand content and well connected sand bodies (Figure 37).

In the north-east of the Gnangara groundwater system, where the South Perth Shale aquiclude is absent, downwards head gradients promote discharge into the Yarragadee aquifer (Figure 41b, see also Pigois 2012). The aquifer strata hosting this flow are dominated by fluvial floodplain and tidal flat facies of the Wanneroo Member with rare channel-fill deposits, and with moderate sand content and poorly connected sand bodies (Figure 37).

In the south-west of the Gnangara groundwater system, the Leederville aquifer is confined and the south-westward hydraulic gradient drives groundwater offshore. Groundwater from the centre of the system with a strong influence from Superficial recharge flows southwest into the offshore Leederville aquifer (flow zones 3 to 5, Figure 35). It is not clear if groundwater from the north-east of the system with a strong influence from regional flow discharges into sandy units within Kings Park Formation (flow zones 6 and 7, Figure 35).

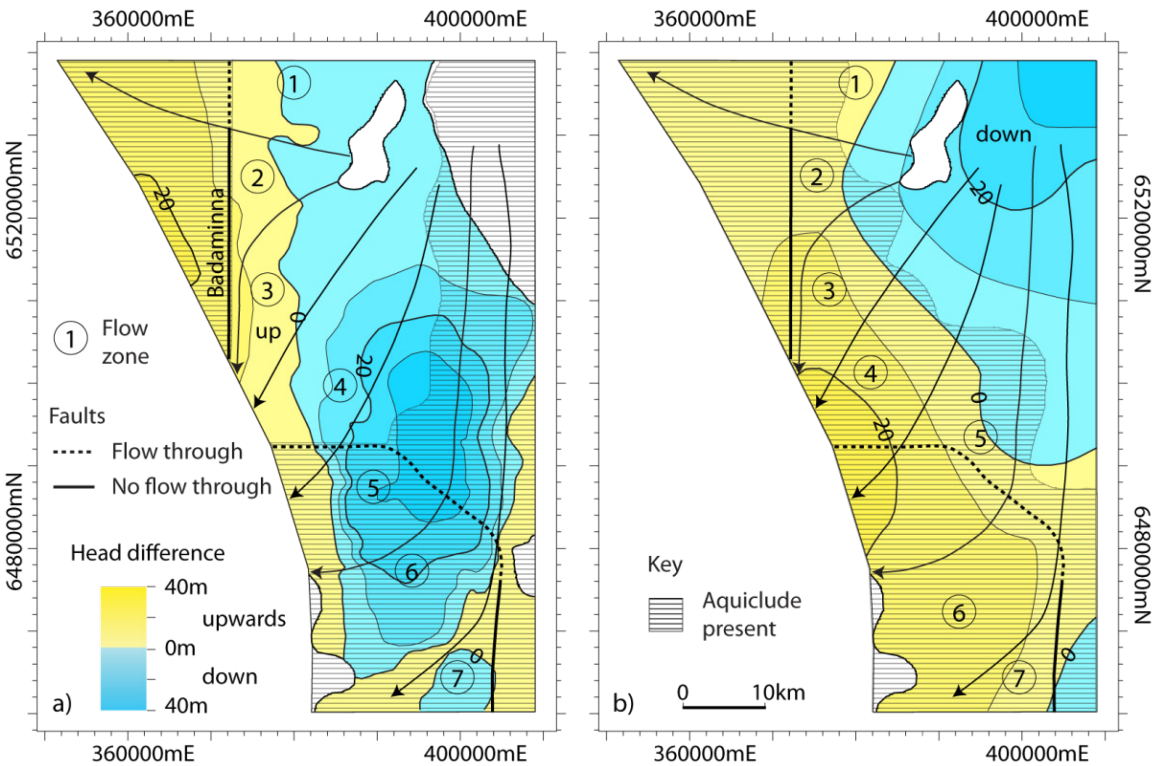


Figure 41 Maps showing aquifer discharge. (a) Upward discharge from Leederville into the Superficial aquifer to the east of the Badaminna Fault, (b) downward discharge from Leederville into the Yarragadee aquifer in the north-east .

5.5 Groundwater salinity distribution

Stratified salinity distribution

In the modelled groundwater salinity distribution for the Leederville aquifer, the lowest salinity groundwater (<250 mg/L) is found at shallow depths in the central northern Gnangara Mound and to the south just across the Wanneroo Fault (Figure 42). The salinity distribution is vertically stratified, with salinity increasing with depth and distance from the low salinity zone, except in the north-west. In the central study area, the salinity at the base of the aquifer increases to ~500 mg/L. In the eastern study area near the Darling Fault and in the south, salinity at the base of the aquifer increases to >1000 mg/L. Overall the modelled salinity ranges from 170 to 3000 mg/L, consistent with the observed salinity range of groundwater samples.

Strong correlation between salinity and age

There is a strong correlation between groundwater age and salinity, and three groundwater bodies are recognised in the Leederville aquifer (Figure 36). The first is a shallow, low salinity groundwater body (<500 mg/L) which is 4 to 6 kyr old. The second is a deeper, marginal to brackish groundwater body (>500 mg/L) which ranges from 10 kyr old in the north to 30 kyr old in the south. The third groundwater body is recognised only in the north-western study area. It exhibits limited vertical stratification of salinity and is old (single data point, 28 kyr) and fresh (<500 mg/L), in contrast to the young, fresh groundwater observed in the rest of the aquifer (Figure 36).

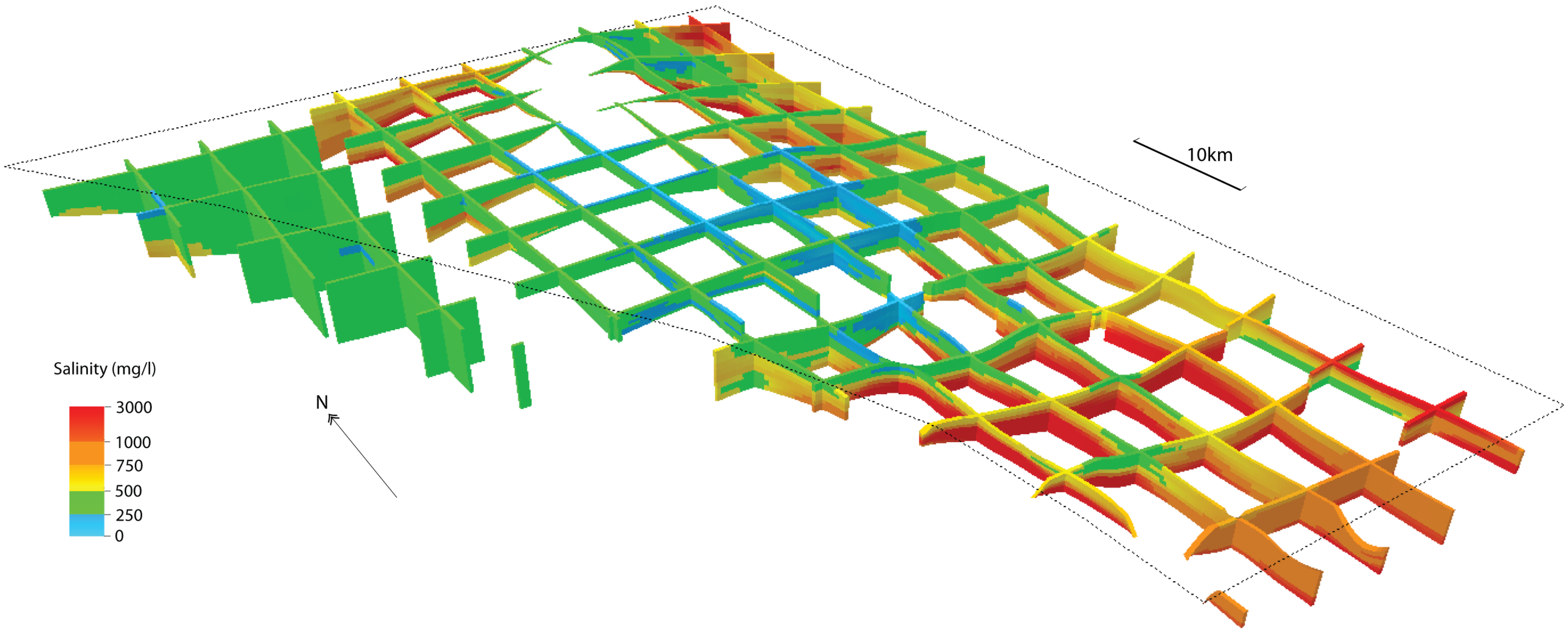


Figure 42 Perspective cut-through 3D view of the Gnangara groundwater system from the south-west showing the stratified groundwater salinity distribution in the Leederville aquifer. The salinity distribution is less stratified in the north-west.

6 Implications for PRAMS

An important aim of this study was to assist in the management of the Gnangara groundwater system. This chapter discusses the differences between the hydrogeological model proposed in this study and the current conceptual model of the Perth regional aquifer modelling system. It also discusses possible improvements of PRAMS and related recommendations.

PRAMS is based on hydrogeology of Davidson (1995) and Davidson and Yu (2006) and includes major and minor aquifers throughout most of the central onshore Perth Basin. In contrast, this study has a much smaller scope, focusing on the Leederville aquifer within the Gnangara groundwater system. This study is based on a similar dataset of archived downhole geophysical logs and groundwater data to that used by Davidson (1995) and Davidson and Yu (2006). However, the dataset in this study has been supplemented by diamond drill core and geophysical logs from recent drilling. The geology of Davidson (1995) and Davidson and Yu (2006) was based primarily on lithostratigraphic interpretations of downhole geophysical logs and drilling chips. This study has incorporated facies analysis of drill core and has interpreted lateral facies arrangements of the Warnbro Group within a sequence–stratigraphic framework.

Sedimentology, facies architecture and gamma ray motifs

The limited descriptions of the sedimentology and gamma ray motifs of the Warnbro Group in Davidson (1995) have led to difficulties in identification and lateral correlation of the Leederville Formation. In this study detailed descriptions of the facies associations, interpreted depositional environments and gamma ray motifs of the Warnbro Group are presented, including lateral variation within the Pinjar and Wanneroo members.

In PRAMS, inverse modelling is used to obtain hydraulic parameters (specific yield, elastic storage and vertical and horizontal hydraulic conductivity) using recorded hydraulic heads and abstraction data (CyMod Systems 2009). Heterogeneity in an aquifer is difficult to capture by these methods because of the low sensitivity of hydraulic heads to variations in hydraulic properties (de Marsily et al. 2005). In fact, head variations due to heterogeneity are small, whereas those due to flow velocities and travel time are large.

It would therefore be useful to incorporate the facies architecture and resultant heterogeneity proposed in this study into PRAMS, to assist in the calibration of hydraulic parameters. The sand percentage distribution is reliable as a description of the relative magnitude of hydraulic parameters, but should not be used to calculate absolute values (Leyland 2011). Heterogeneity can be incorporated by the zonation method, a common technique in large scale models whereby parameterisation is accomplished by partitioning the domain into a set of subdomains (e.g. Carrera et al. 2005). Zonation is already employed during PRAMS calibration, and at present the geometry of the zones and the magnitude of the hydraulic parameters are determined by the modeller (CyMod Systems 2009). The facies architecture and depositional connectivity proposed in this study can be used to influence the zone geometry and relative magnitude of hydraulic parameters. This geologically based inversion process involves a series of iterative, subjective decisions. Moreover, it requires good communication between the geologist and the modeller and it needs to be thoroughly documented (Carrera et al. 2005). An alternative way of incorporating the facies architecture described in this study would be by geostatistical modelling of the sand bodies (e.g. de Marsily et al. 2005).

Another possible application of the facies architecture and sequence-stratigraphic framework proposed in this study is to perform qualitative downscaling when a new sub-model is needed (e.g. Scharling et al. 2009). This study provides a conceptual framework for small scale models to be developed within the study area, using analogue deposits to deepen the understanding of local heterogeneity. This would be useful to projects such as geothermal investigations and aquifer re-injection trials.

Aquifer thickness and distribution

The lateral distribution, depth and thickness of Warnbro Group strata in this study are similar to the hydrogeology of Davidson and Yu (2006), but there are some significant differences. Recognition of lateral facies variation has led to changes in interpreted depth and thickness within the Wanneroo and Pinjar members, especially in the eastern study area. In this study the distribution of the Pinjar Member is more restricted across the recharge window where the overlying Coolyena Group is absent. The Pinjar Member acts as an aquitard, and its reduced distribution represents a larger recharge area for the Leederville aquifer than previously thought. This constitutes an increased vulnerability to contamination in the Leederville aquifer, and an increased susceptibility to drawdown in the Superficial aquifer.

It is recommended that further data be collected in the south-east of the Leederville aquifer recharge window, where the Coolyena Group aquiclude is absent but three bores (AM18, AM22 and Pinjar 17) indicate the presence of aquitard facies associations of the Pinjar Member. The distribution of the Pinjar Member is poorly constrained and may influence recharge and drawdown patterns.

Structural features

The depth, thickness and connectivity of the strata are also different from those used in PRAMS in the region of interpreted faults. The fault offset and overall eastward dip of Cretaceous strata proposed in this study are in contrast to the gently folded and draped interpretation used in PRAMS, especially in the north-western study area in the region of the Badaminna Fault. Fault block juxtaposition is an important control on aquifer connectivity, as was recognised in the Perth Basin by Commander (1974) and Commander (1975). In the PRAMS model, the Leederville and Yarragadee aquifers are laterally continuous and separated from each other by a thin, west dipping interval of the South Perth Shale and the Mariginiup Member. In this study, fault block juxtaposition results in hydraulic isolation of the western and eastern portions of the Leederville aquifer and also results in flow from the Yarragadee to the Leederville aquifer.

This represents a more complex aquifer connectivity than previously thought and this could affect the drawdown predictions for planned groundwater abstraction from Gnangara groundwater system. It would be useful to incorporate the fault offset proposed in this study into PRAMS. During this procedure, it is recommended that more data be collected in the region of the faults, including a comparison of the chemical compositions of groundwater in the Leederville and Yarragadee aquifers, to address uncertainties in the proposed fault block juxtaposition and fault zone characteristics (Manzocchi et al. 2008).

Further investigations

Further investigation into the flow and recharge patterns in the Leederville aquifer could be carried out through inverse geochemical modelling of salinity, using the salinity distribution described in this study as the final compositional distribution (e.g. Glynn & Plummer, 2005). This would improve the conceptual understanding of the Leederville aquifer, and would assist in the calibration of hydraulic parameters in PRAMS. A comprehensive survey of groundwater ages and a mixing model would also help understand the paleorecharge and flow patterns of the Leederville aquifer (e.g. Edmunds 2001).

7 Conclusions and recommendations

7.1 Conclusions

This report presents a 3D geological and hydrogeological model of the Leederville aquifer. The model contributes to the hydrogeological understanding of the Gnangara groundwater system, providing a basis for the calibration, assessment and future modification of PRAMS, thereby helping to create a reliable groundwater management tool.

The conclusions of the study are summarised below.

- An overall tidally influenced deltaic depositional setting is proposed for the Warnbro Group, based on facies analysis of 300 m of drill core. Maps of facies variation show facies architecture developed parallel to the Darling Fault, based on analysis of 158 geophysical logs. New isopach maps are presented for the strata of the Warnbro Group, and detailed descriptions of the gamma ray motifs and sedimentology are presented.
- The Wanneroo Member, which constitutes the majority of the Leederville aquifer, is composed of delta plain deposits. Well connected, tidally influenced sand bodies are well developed and poorly connected, fluvial sand bodies are restricted to the eastern margin.
- The uppermost Pinjar Member is dominated by silt-rich, offshore aquitard facies with poorly connected sand layers. Sand-rich, shoreface aquifer facies are restricted to the eastern study area.
- The Pinjar aquitard facies subcrop the Superficial aquifer less than previously thought. There is significant connection between the Wanneroo aquifer facies and the Superficial aquifer below the crest of the Gnangara Mound, including in the west where the Leederville discharges to the Superficial aquifer.
- The thickness and distribution of the Warnbro and Coolyena groups were influenced by fault activity. The strata dip and thicken towards the downthrown side of the Badaminna, Serpentine and Darling faults, and the previously unrecognised Wanneroo Fault. This indicates syn-depositional fault activity.
- This structural interpretation highlights the likelihood of increased connectivity between the Leederville and Yarragadee aquifers, and local hydraulic isolation of the Leederville aquifer. This is especially true in the north-western study area along the Badaminna Fault.
- A comprehensive, 3D salinity distribution of the Leederville aquifer is presented for the first time, based on 124 resistivity logs. The distribution of the freshest water highlights the recharge zone below the crest of the Gnangara Mound. The contrasting salinity distribution on either side of the Badaminna Fault highlights the hydraulic isolation of the offset portions of the Leederville aquifer.

- Two flow paths have been recognised that highlight the two main sources of groundwater in the Leederville aquifer: a shallow, fresh, young flow path associated with recent recharge, and a deeper, marginal to brackish, old flow path fed by regional flow from the north.

7.2 Recommendations

Most of the recommendations from this study relate to possible improvements of the PRAMS conceptual model. These recommendations could be addressed during future redevelopment of PRAMS, and are subject to the priorities of the Department of Water and the availability of resources.

- It would be useful to incorporate the proposed facies architecture and heterogeneity into PRAMS. This could be done during parameterisation prior to calibration, by using the facies architecture to outline the parameter zones and by using the descriptions of sand-body connectivity and sand percentage to define the relative, but not absolute, magnitude of hydraulic parameters in each zone.
- It is recommended that the isopachs in PRAMS be amended according to the new isopachs maps, in particular the reduced distribution of the Pinjar Member below the crest of Gnangara Mound.
- It would be helpful to collect more data along the eastern margin of the Leederville aquifer recharge window, to better constrain the distribution of the Pinjar aquitard facies.
- It is also recommended that the proposed fault offsets are incorporated into PRAMS. The hydraulic properties of the fault zone should be carefully considered, and a range of alternative fault zone geometries should be analysed during model redevelopment. It is recommended that more data be collected in the region of the faults to better determine the hydraulic properties of the fault zone.
- Further investigation into the flow and recharge patterns in the Leederville aquifer could be carried out through inverse geochemical modelling of salinity, using the salinity distribution described in this study as the final compositional distribution.

Appendices

Appendix A — Facies associations

Nineteen facies were identified in drill cores from AM26E and BNYP 1/07 (Leyland 2011) and these facies have been grouped into seven facies associations (FA1 to FA7). A summary of their characteristic facies, stacking patterns and their interpreted depositional environments is presented below. The facies associations are shown on the summary log (Figure 43) and on detailed logs in figures 44 and 45.

FA1: Fining-upward, cross-stratified very coarse to very fine sands

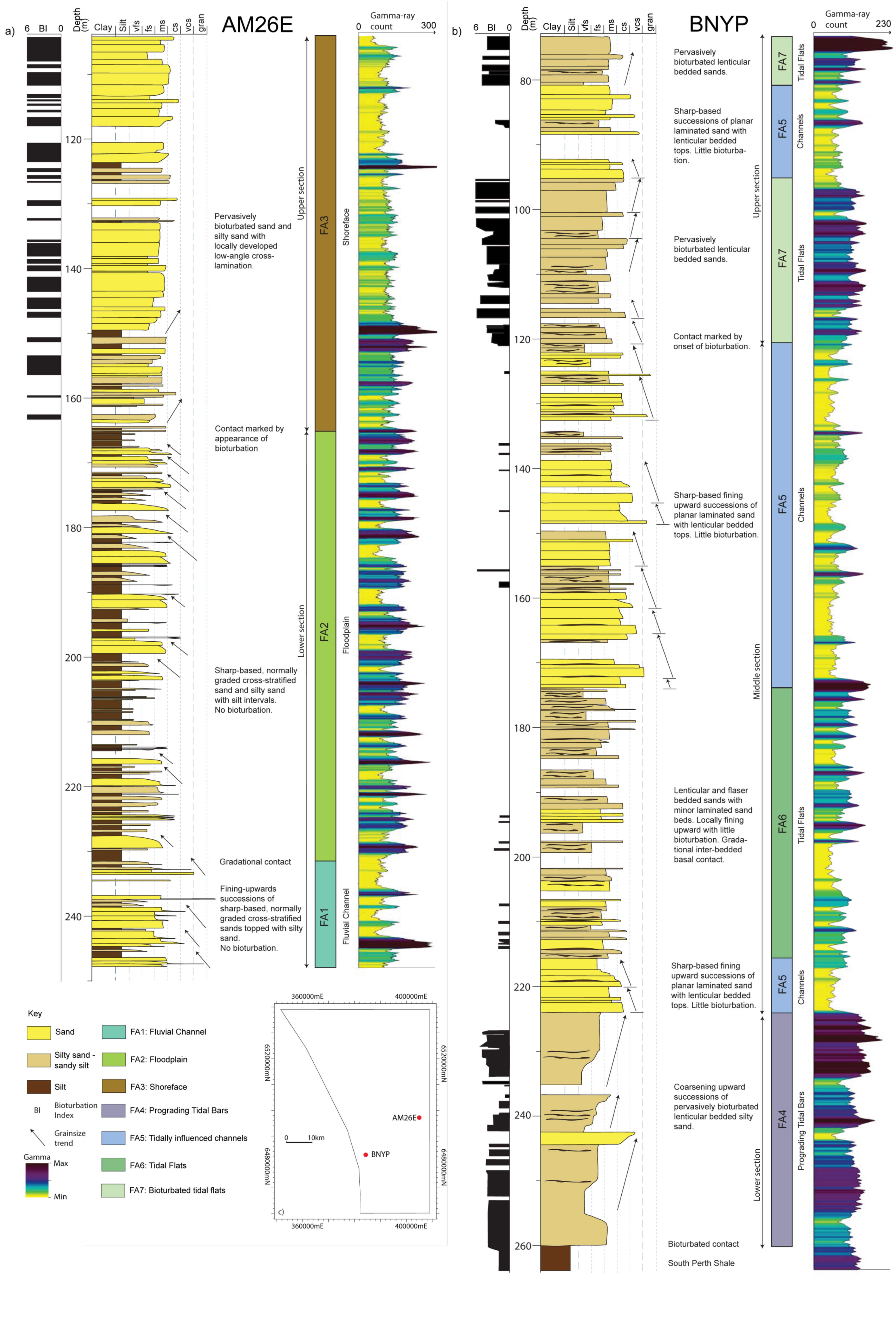
Description

FA1 is characterised by stacked, ~5 m thick, fining-upward intervals of sandstone (figures 43a and 44a). Each interval is dominated by thickly bedded, normally graded coarse to medium sands featuring small-scale cross-bedding and ripple cross-lamination. The base of each interval and most bedding planes are sharp, scoured and commonly overlain by very coarse, locally granular lags with rip-up clasts. The top of each interval is composed of 1 to 2 m of normally graded, fine to very fine silty sand, featuring rare root remnants. No marine palynomorphs were recovered and no bioturbation was observed.

Interpretation

The presence of root remnants suggests a terrestrial setting (e.g. Bridge 2006) which is supported by the absence of marine palynomorphs. There is no evidence for tidal current activity or current reversals such as herringbone, lenticular or flaser bedding, which is consistent with fluvial conditions (e.g. Dalrymple 1992).

The scoured bases, fining-upward character and silty, fine sand top of each interval and the dominance of lower flow regime sedimentary structures is typical of channel deposits of mixed-load rivers carrying both bedload sand and suspended silt (e.g. Collinson 1996). The ~5 m thick, fining upward intervals are interpreted as single channel fills, deposited by lateral or downstream accretion of sandy channel bars followed by progressively weaker flows during filling (e.g. Bridge 2006). Scouring at the bases of sand beds is interpreted as erosion during flood events. The stacked channel fills are interpreted as a fluvial channel-fill complex with a total thickness of 15 m. This is within the typical thickness range of braided (5 to 60 m) or meandering (4 to 20 m) river channel-fill complexes as summarised by Gibling (2006).



a)
AM26E
6 BI 0
Depth (m)
Clay Silt vfs fs ms cs vcs gran
Gamma-ray count
0 300
Pervasively bioturbated sand and silty sand with locally developed low-angle cross-lamination.
Contact marked by appearance of bioturbation
Sharp-based, normally graded cross-stratified sand and silty sand with silt intervals. No bioturbation.
Gradational contact
Fining-upwards successions of sharp-based, normally graded cross-stratified sands topped with silty sand. No bioturbation.
Upper section
Lower section
FA3
FA2
FA1
Shoreface
Floodplain
Fluvial Channel
b)
BNYP
Pervasively bioturbated lenticular bedded sands.
Sharp-based successions of planar laminated sand with lenticular bedded tops. Little bioturba-tion.
Pervasively bioturbated lenticular bedded sands.
Contact marked by onset of bioturbation.
Sharp-based fining upward successions of planar laminated sand with lenticular bedded tops. Little bioturbation.
Lenticular and flaser bedded sands with minor laminated sand beds. Locally fining upward with little bioturbation. Grada-tional inter-bedded basal contact.
Sharp-based fining upward successions of planar laminated sand with lenticular bedded tops. Little bioturbation.
Coarsening upward successions of pervasively bioturbated lenticular bedded silty sand.
Bioturbated contact
South Perth Shale
Upper section
Middle section
Lower section
FA7 FA5 FA7 FA5 FA6 FA5 FA4
Tidal Flats
Channels
Tidal Flats
Channels
Tidal Flats
Channels
Prograding Tidal Bars
0 230
Key
Sand
Silty sand - sandy silt
Silt
BI Bioturbation Index
Grainsize trend
Gamma Max Min
FA1: Fluvial Channel
FA2: Floodplain
FA3: Shoreface
FA4: Prograding Tidal Bars
FA5: Tidally influenced channels
FA6: Tidal Flats
FA7: Bioturbated tidal flats
c)
360000mE
400000mE
6520000mN
6480000mN
0 10km
AM26E
BNYP

Previous page: Figure 43 Log showing grain size trends, bioturbation index, sedimentary features, facies associations and downhole gamma ray logs of (a) AM26E and (b) BNYP 1/07, (c) map showing core locations. Note: due to core slippage, depth of core at bottom of AM26E is ~2 m lower than on gamma ray log

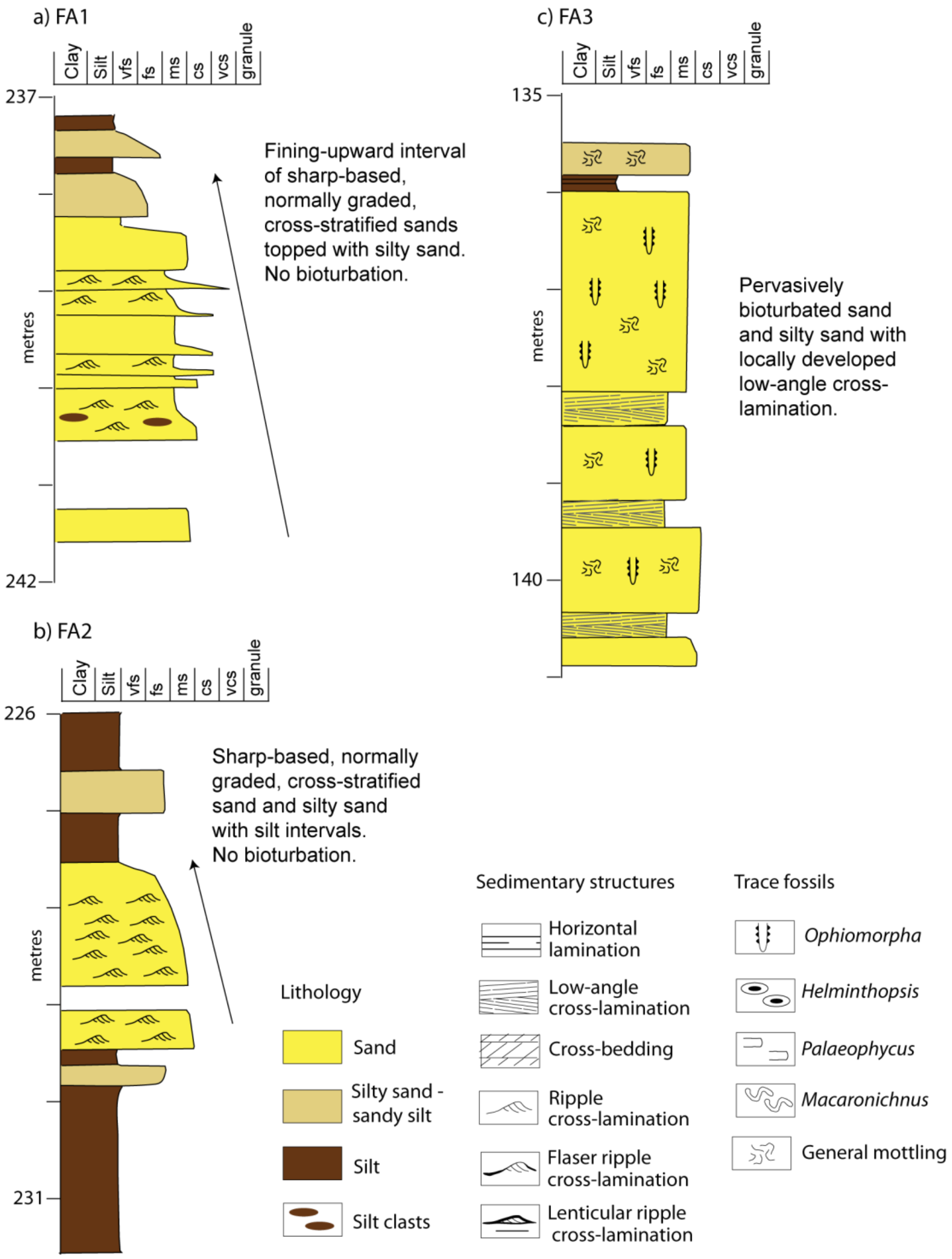


Figure 44 Representative intervals of AM26E, showing characteristic features of FA1 to FA3, depth in metres below ground. (a) FA1, showing a 5 m thick, fining-upward interval of sharp-based, cross-stratified sands. (b) FA2, showing a 2 m thick, fining-upward interval of cross-stratified sand and 2 m thick intervals of silt. (c) FA3, showing pervasively bioturbated sand with low-angle cross-lamination.

FA2: Fining-upward, cross-stratified medium to very fine sands with silt intervals

Description

FA2 is characterised by 2 to 4 m thick, sharp-based, fining-upward intervals of sandstone (figures 43a and 44b). These intervals are composed of thickly bedded, normally graded medium to very fine sands and silty sands featuring small-scale cross-bedding and ripple cross-lamination. These facies are intercalated with 2 to 10 m thick intervals of massive or locally laminated silt with rare root remnants. Overall, FA2 is composed of near equal proportions of medium to very fine sand (30%), silty sand (30%) and silt (40%). No marine palynomorphs have been recovered.

Interpretation

The fining-upward trends and sedimentary structures indicate deposition in small abandoned crevasse channel fills and as proximal crevasse splay deposits (e.g. Bristow et al. 1999; Perez-Arlucea & Smith 1999). The 2 to 4 m thickness is within the typical thickness range (0.2 to 17 m, average 2 m) of crevasse channel and splay sand bodies (Gibling 2006). The intervals of massive, locally laminated silt are interpreted as overbank silts and clays (e.g. Bridge 2006). These are typical overbank deposits of an idealised mixed-load river, where increased bank stability means levees are breached periodically during flood (e.g. Collinson 1996) and FA2 is interpreted as floodplain deposition. The presence of root remnants indicates a terrestrial setting (e.g. Bridge 2006) which is consistent with the absence of marine palynomorphs.

FA3: Bioturbated, coarsening-upward fine to medium sands

Description

FA3 is characterised by pervasively bioturbated, very thickly bedded fine to medium sands (figures 43a and 44c) with abundant *Ophiomorpha*. This facies is intercalated with thickly bedded, bioturbated, fine to medium silty sands and fine, low-angle cross-laminated sands. There is an overall coarsening-upward trend from fine to medium sand and silty sand to medium, locally coarse sand (Figure 43a). Palynomorphs are typically of terrestrial origin with a few marine species.

Interpretation

Abundant *Ophiomorpha* in low-angle cross-laminated sands are typical of rapid colonisation of shifting sands deposited in wave influenced shoreface or upper flow regime conditions, although *Ophiomorpha* is also recognised in non-marine settings (e.g. Walker et al. 1993; Pollard et al. 1993). A shallow marine setting is indicated by the abundance of terrestrial palynomorphs with a few marine species. This association is interpreted to represent shoreface deposition and the overall coarsening-upward trend is interpreted as a gradual shift to increasingly high energy conditions from lower to upper shoreface (e.g. Walker et al. 1993; Clifton 2006; Mitchell et al. 2006).

FA4: Coarsening-upwards, bioturbated, lenticular bedded very fine to medium silty sand

Description

FA4 is characterised by 8 to 12 m thick, sharp-based intervals that coarsen upwards from very fine to medium, locally coarse silty sand (figures 43b & 45a). The intervals also exhibit an upward decrease in silt matrix from 40 to 20%. They are dominated by lenticular bedding with abundant dwelling burrows of the *Skolithos* ichnofacies. There is also minor laminated fine sand with *Macaronichnus*. Ichnological diversity is moderate but lower than typical in open marine assemblages (e.g. Bann & Fielding 2004). Palynomorphs are typically of terrestrial origin with a few marine species.

Interpretation

Thick (~10 m) intervals of lenticular bedded heterolithic facies typically form in environments with a strong tidal influence (e.g. Dalrymple 1992) and coarsening-upward trends suggest migrating or prograding tidal bars. These bars may represent mouth bars of active distributaries (e.g. McIlroy 2004), tidal channel bars migrating downstream (e.g. Fenies & Tastet 1998), or tidal channel point-bar deposits (e.g. Pearson & Gingras, 2006).

Dwelling burrows typical of the *Skolithos* ichnofacies suggest a moderate energy, shallow marine environment (e.g. Pemberton et al. 2001) and *Macaronichnus* indicate episodes of high energy (e.g. Seike 2007; Carmona et al. 2009). The intermediate faunal diversity and pervasive bioturbation indicate moderately stressed marine conditions (e.g. MacEachern et al. 2005). These ichnological characteristics are typical of distributary mouth bars and this association is interpreted as stacked, prograding distributary mouth bars with a strong tidal influence (e.g. Bann & Fielding 2004; McIlroy 2004). The abundance of terrestrial palynomorphs with few marine species supports a nearshore setting with marine and terrestrial influences.

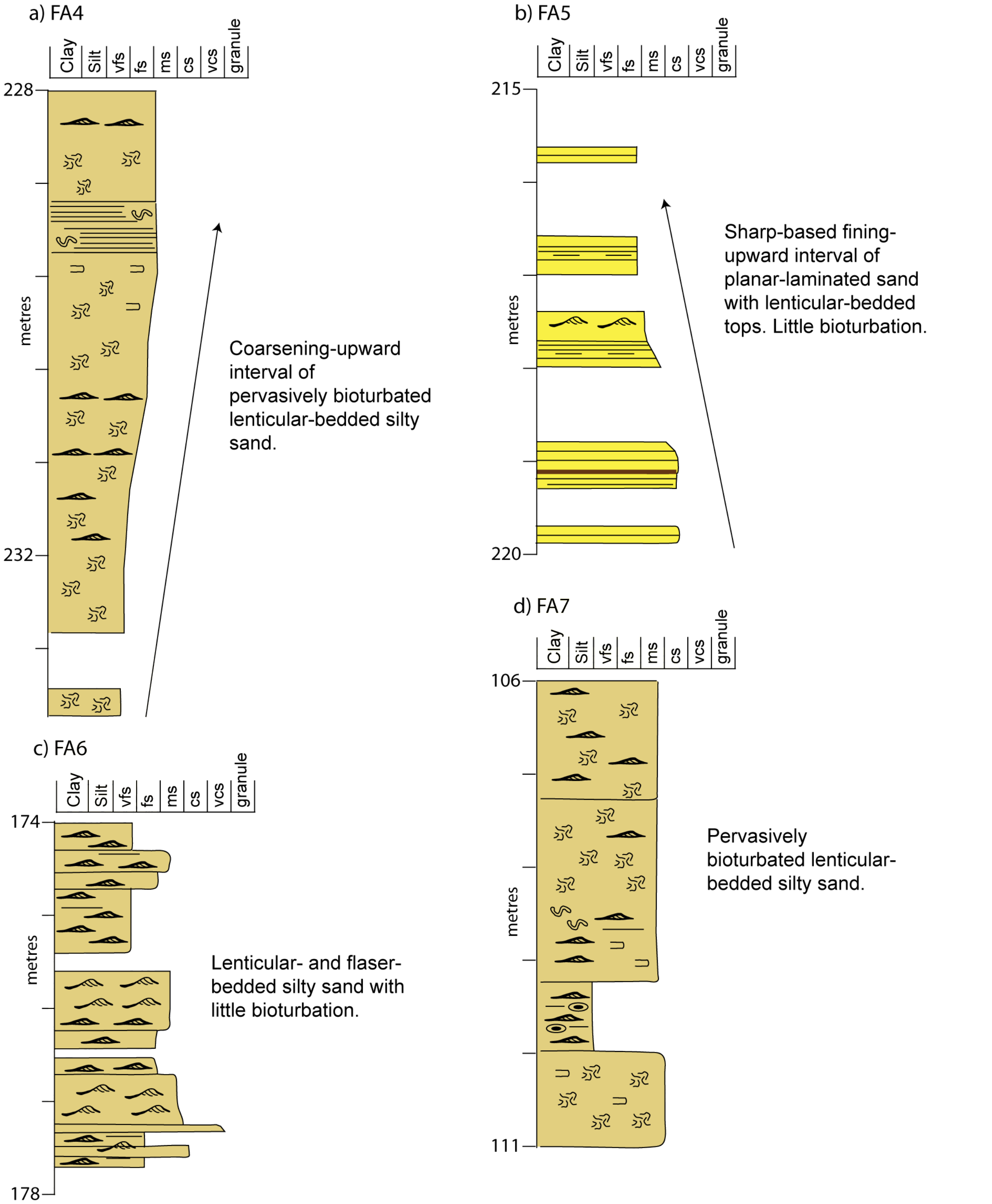


Figure 45 Representative intervals of BNYP, showing characteristic features of FA4 to FA7, depth in metres below ground. (a) FA4, showing a 7 m thick, coarsening-upward interval of bioturbated, lenticular bedded silty sand. (b) FA5, showing a 5 m thick, fining-upward interval of planar-laminated sand with silt drapes and minor lenticular bedding. (c) FA 6, showing lenticular and flaser bedded silty sand. (d) FA7, showing pervasively bioturbated silty sand with remnant lenticular bedding. Key in Figure 44.

FA5: Fining-upward planar-laminated sands

Description

FA5 is characterised by 3 to 8 m thick, sharp-based, typically fining-upward intervals of predominantly planar-laminated sand (figures 43b & 45b) A typical interval features a coarse, laminated base with rare silt drapes, and minor massive or small-scale cross-bedded sand. The medium, locally fine grained top of the interval is dominated by laminated sand and lenticular or flaser bedded silty sands with rare dwelling burrows of the *Skolithos* ichnofacies. Palynomorphs are predominantly of terrestrial origin with a few marine species.

Interpretation

Dominant plane bed sands with rare silt drapes and lenticular bedding indicate strong currents with episodes of tidally influenced, moderate to low energy deposition (e.g. Dalrymple 1992). Abundant terrestrial palynomorphs with few marine species are consistent with a nearshore marine setting with significant terrestrial input.

The sharply scoured base, fining-upwards trend and lenticular bedded top are interpreted as tidally influenced channel-fill sands deposited in decreasing energy conditions (Ponten & Plink-Bjorklund 2007; Bhattacharya 2006; McIlroy 2004). A modern example is the channelised, tidally influenced deposits in the mesotidal Mahakam delta in Indonesia, where sand rich strata are focused in areas dominated by fluvial currents (Storms et al. 2005). This suggests currents active during deposition of FA5 had a significant fluvial influence (e.g. Ponten & Plink-Bjorklund 2007; McIlroy 2004).

FA6: Lenticular and flaser bedded sands

Description

FA6 is composed of heterolithic facies with limited bioturbation and an overall aggradational trend (figures 43b and 45c). The association is dominated by lenticular to flaser bedded, fine to medium silty sand with locally scoured surfaces and coarse sand beds and with rare dwelling burrows of the *Skolithos* ichnofacies. In addition there are minor 1 to 4 m thick intervals of laminated medium sand with locally well developed *Macaronichnus*. There are also minor 1 to 2 m intervals of laminated very fine sand and silt with a few *Helminthopsis* traces. Palynomorphs are typically of terrestrial origin with a few marine species.

Interpretation

Dominant lenticular and flaser bedded heterolithic facies with locally scoured surfaces, upper flow regime sands and low energy silts indicate fluctuating energy conditions. This is typical of environments with a strong tidal influence (e.g. Dalrymple 1992) and FA6 is interpreted to represent extensive tidal sand and mud flats (e.g. Mangano & Buatois, 2004). Limited bioturbation suggests biological stress due to fluctuating salinity or periodic subaerial exposure (e.g. MacEachern et al.

2005; McIlroy 2004). A nearshore marine setting is indicated by the presence of both terrestrial and marine palynomorphs.

FA7: Bioturbated lenticular bedded sands and silts

Description

FA7 is characterised by extensively bioturbated heterolithic facies with an overall aggradational trend (figures 43b and 45d). The association is dominated by mottled fine to medium silty sand and sandy silt with abundant overlapping dwelling burrows of the *Skolithos* ichnofacies and with local remnant lenticular bedding. Ichnological diversity is moderate, but is lower than in typical open marine assemblages (e.g. Bann & Fielding 2004). There are minor ~1 m thick intervals of laminated very fine sand and silt with *Helminthopsis*. Palynomorphs are typically of terrestrial origin with a few marine species. Accessory glauconite was present in a sample from the top of FA7.

Interpretation

Remnant lenticular bedding indicates fluctuating depositional energy, which is interpreted to represent tidally influenced conditions (e.g. Dalrymple 1992). This is consistent with a nearshore marine setting indicated by the presence of abundant terrestrial palynomorphs with a few marine species, and by the presence of glauconite (Kelly & Webb 1999). Dwelling burrows typical of the *Skolithos* ichnofacies suggest a moderate-energy shallow marine environment (e.g. Pemberton et al. 2001). Intermediate ichnological diversity and extensive bioturbation suggests moderately stressed, tidal flat deposition (e.g. McIlroy 2004; Bann & Fielding 2004; MacEachern et al. 2005).

Gamma ray log motifs

In the lower section of AM26E (248 m to 165 m depth), the downhole gamma ray log zigzags from low to high gamma ray count with 2 to 10 m between symmetrical peaks (Figure 43a). Throughout most of this section (232 m to 165 m depth) the log is dominated by high gamma ray count, corresponding to silt-rich (60%–90%) intervals in the floodplain association FA2. At the base (248 m to 232 m depth) the log is dominated by 5 to 6 m intervals of low gamma ray count, corresponding to the sand-rich intervals in the fluvial channel-fill association FA1.

In the upper section of AM26E (165 m to 104 m depth) the downhole gamma ray log is dominated by low gamma, corresponding to the sand-rich (typically <30% silt) shoreface association FA3 (Figure 43a). There is an upwards decrease in gamma ray count overall, which corresponds to the upwards decrease in silt content observed in FA3, illustrating that gradual changes in silt content at a 10 m scale are also discernible on the gamma ray logs.

In the lower section of BNYP (260 m to 244 m depth) the downhole gamma ray log is characterised by 8 to 12 m thick, sharp based, bell-shaped intervals dominated by high gamma (Figure 43b). In each interval gamma ray count decreases upwards to moderate, locally low gamma, corresponding to the coarsening-upward trend of the stacked tidal bars of FA4.

In the middle and upper sections of BNYP (224 m to 73 m depth) the downhole gamma ray log is characterised by 10 to 50 m thick, blocky intervals of low gamma, corresponding to the sand-rich (<20% silt) intervals of the tidally-influenced channel-fills association FA5 (Figure 43b). They are intercalated with 10 to 40 m thick intervals that zigzag from low to moderate gamma ray count, with 5 to 15 m between symmetrical peaks, corresponding to the heterolithic facies (typically 30%–70% silt) in the tidal flat associations FA6 and FA7.

Overall, the primary influence on the gamma ray motif is the thickness and vertical distribution of sand-rich intervals (<20% silt) in different facies associations, which control the distribution of low radiation intervals. The very high gamma ray count peak in BNYP at 74 m depth corresponds to the presence of glauconite and elevated zircon content (Leyland 2011). Similar spikes in radiation above the shale line on the downhole gamma ray log are interpreted as glauconitic strata or horizons where zircon and monazite have been locally concentrated due to their high specific gravity. The maximum and minimum gamma ray counts are consistent throughout the Warnbro Group, which suggests that the composition of the group is also consistent throughout.

Appendix B — Strata depths

Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	**Surface (m below ground)**	Valanginian Unconformity	Base Kws	Base Kwlm	Base Kwlw	Base Kwlp	Aptian Unconformity	Paleocene Unconformity	Quaternary Unconformity
AM01	356924	6531829	53	793		594	517	505	499	216	216	::::	99
AM02	365646	6529649	36	881		867	797	755	693	219	207	61	61
AM02A	365659	6529664	37	515		--	--	--	--	220	210	61	61
AM03	367173	6535521	27	729		780	694	671	606	163	163	::::	39
AM04	383790	6535459	50	549		279	203	203	189	41	41	::::	41
AM04A	383765	6535457	50	549		268	206	206	191	41	41	::::	41
AM05	375480	6527971	52	302		306	276	256	240	52	52	::::	52
AM06	386985	6529614	64	300		56	56	56	56	56	56	::::	56
AM07	398727	6527718	102	718		307	307	307	307	113	20	::::	::::
AM08	368988	6522790	52	809		994	943	886	823	371	341	162	75
AM09	380917	6522375	59	303		233	203	193	183	57	57	::::	57
AM10	392249	6521848	69	298		70	70	70	70	51	51	::::	51
AM11	406614	6525106	190	810		741	741	741	741	344	260	::::	::::
AM12	368581	6511653	16	838		1055	996	931	864	415	373	191	45
AM13	374909	6516946	54	798		330	299	272	259	65	65	::::	65
AM14	386758	6516658	75	810		207	171	171	161	69	69	::::	69
AM15	400874	6517429	69	784		455	366	366	366	139	97	::::	20
AM17	384288	6510078	72	301		210	199	181	168	80	80	::::	80
AM18	397130	6510141	77	300		--	--	--	--	104	69	::::	69
AM18A	399959	6510643	60	678		485	370	370	370	144	102	::::	51
AM19	405304	6507016	69	802		501	397	397	397	208	148	::::	27
AM20	377567	6500435	29	467		340	340	242	192	55	55	::::	55
AM21	387307	6503748	59	464		228	218	192	172	60	60	::::	60
AM22	395222	6501479	82	589		517	370	348	315	116	64	::::	64
AM23	380419	6493089	29	420		335	335	239	190	46	46	::::	46
AM24	389763	6491300	50	908		907	799	491	417	223	157	::::	56
AM25	396157	6494906	73	605		613	432	392	343	150	144	::::	69
AM26	404955	6497166	37	673		525	354	354	354	165	99	::::	28
AM26A	404909	6497609	38	366		--	--	--	--	171	106	::::	34
AM26B	404929	6497309	37	374		--	--	--	--	170	107	::::	32
AM26E	404909	6497207	37	249		--	--	--	--	165	105	::::	32
AM27	384680	6483682	34	762		513	394	303	273	96	96	::::	59
AM28	392620	6485039	53	624		--	--	561	503	293	224	::::	60
AM29	402291	6491061	48	758		652	469	469	469	264	183	::::	54
AM30	402431	6482066	50	747		772	636	545	500	318	206	::::	32
AM30Z	397699	6478981	39	555		--	--	--	507	332	226	::::	34

-- Surface depth below base of well, :::: Surface depth equal to overlying surface or ground,
* Surface present, depth not interpreted, Co-ordinate system: Geocentric Datum of Australia Zone 50

					Surface (m below ground)							
Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	Valanginian Unconformity	Base Kws	Base Kwlm	Base Kwlw	Base Kwlp	Aptian Unconformity	Paleocene Unconformity	Quaternary Unconformity
AM31	406171	6480712	6	800	553	428	395	333	185	97	::::	6
AM31A	406168	6480700	6	211	--	--	--	--	184	91	::::	5
AM32	383037	6473764	13	404	--	293	238	::::	::::	::::	228	44
AM33A	385155	6477330	7	533	492	379	309	264	127	117	51	35
AM34A	394664	6474341	41	734	740	638	539	495	303	214	::::	46
AM35A	403601	6475592	17	649	671	558	493	450	267	144	::::	20
AM36	387766	6470299	16	616	525	401	297	276	132	114	37	37
AM37A	398469	6469322	21	1000	815	676	578	540	339	201	::::	29
AM38	404509	6468849	11	244	--	--	--	--	201	63	::::	11
AM38A	404921	6468931	11	551	537	420	394	334	200	62	::::	11
AM40	394744	6460282	23	740	748	613	517	493	::::	::::	388	33
AM41	404135	6460863	21	504	522	400	363	327	187	94	69	23
Albert St	388989	6472389	18	741	607	478	382	359	184	150	::::	38
Amelia St	387279	6473049	17	297	--	--	--	284	130	119	::::	37
Avon Valley	398039	6527349	120	231	--	--	--	--	101	23	::::	3
Badaminna (deep oil)	373216	6531740	37	2438	297	278	259	241	44	44	::::	44
Balcatta 2	388699	6471229	16	732	553	450	360	346	168	155	::::	39
Barragoon (deep oil)	365500	6529515	40	2335	874	803	762	698	223	212	64	64
Baskerville Oval 1	406814	6481906	22	229	--	--	--	--	149	44	::::	12
Beenyup 1/07	384261	6482827	21	345	--	--	263	224	71	71	::::	43
Bold Park 1	383919	6467519	13	763	433	299	226	169	::::	::::	124	43
Bold Park 2	384309	6466369	28	779	453	::::	::::	::::	::::	::::	327	60
Bullsbrook (deep oil)	389922	6516851	91	4257	160	160	160	153	91	91	::::	91
Claremont Asylum 2	384800	6463145	30	642	--	--	--	--	--	--	560	54
Craige Production	384286	6481660	19	804	445	350	287	245	80	80	::::	45
Cullalla 1	406858	6538132	179	800	729	729	729	729	218	160	::::	::::
Eclipse 1 (deep oil)	393254	6521877	78	3660	105	105	105	105	68	68	::::	68
G17	383598	6474795	28	945	444	327	238	212	::::	::::	188	61
G27	383561	6469361	5	750	421	303	207	174	::::	::::	100	43
G7	386820	6473223	12	745	496	402	317	294	147	135	37	37
Gingin 1/75	396339	6532249	115	275	171	171	171	171	0	0	::::	0
Gingin Ashby	398539	6528649	115	189	--	--	--	--	110	21	::::	::::
Gingin Brook No 1	401258	6530836	117	544	456	456	456	456	130	100	::::	::::
Gingin Brook No 2	386834	6534270	58	913	208	168	168	152	56	56	::::	56
Gingin Brook No 3	375859	6535424	31	729	450	376	360	322	34	34	::::	34
Gingin Brook No 4	361828	6534062	10	536	648	578	560	538	164	164	::::	46
Gingin Brook No 5	395400	6533465	104	516	87	87	87	87	0	0	::::	0

-- Surface depth below base of well, :::: Surface depth equal to overlying surface or ground,
* Surface present, depth not interpreted, Co-ordinate system: Geocentric Datum of Australia Zone 50

Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	Surface (m below ground)							
					Valanginian Unconformity	Base Kws	Base Kwlm	Base Kwlw	Base Kwlp	Aptian Unconformity	Paleocene Unconformity	Quaternary Unconformity
Gwelup 10	387191	6475035	17	363	--	--	323	303	153	136	::::	39
Gwelup 125/87	389017	6472328	18	214	--	--	--	--	184	150	::::	38
Gwelup 135	388759	6471189	23	305	--	--	--	--	167	154	::::	47
Gwelup 15	387189	6475029	16	305	--	--	--	--	160	146	::::	42
Gwelup 55	387147	6473813	13	302	--	--	--	--	166	148	::::	37
Gwelup 65	386819	6473279	14	248	--	--	--	--	148	135	::::	*
Hector St	388398	6469562	16	225	--	--	--	--	157	138	::::	38
Houghtons 2	406409	6474949	14	205	--	--	--	--	188	70	::::	4
Lambert 1/81	403939	6508849	60	267	--	--	--	--	208	145	::::	19
Leederville 5	391166	6465067	16	942	715	543	452	415	236	::::	204	30
Leederville 6	390590	6465677	15	695	714	543	452	415	237	::::	205	*
Lexia 52	402970	6485078	44	247	--	--	--	--	--	175	::::	45
Lilac Hill 2	402742	6470949	3	200	--	--	--	--	--	104	::::	5
Loftus St 1	390739	6465649	17	578	--	542	455	415	::::	::::	275	*
Loftus St 2	390739	6465649	17	625	--	545	454	415	::::	::::	282	*
McKechnie 1	401021	6531105	119	270	--	--	--	--	112	91	::::	::::
Midland 1	407490	6467213	35	355	--	--	--	--	203	133	::::	28
Mirrabooka 1	393720	6476397	42	716	713	579	486	452	271	197	::::	52
Mirrabooka 115	395669	6477989	38	391	--	--	--	--	282	206	::::	40
Mirrabooka 15	393605	6476120	35	402	--	--	--	--	265	197	::::	36
Mirrabooka 2	393056	6476728	87	832	721	642	572	530	324	252	::::	92
Mirrabooka 285	402314	6479810	35	527	702	593	522	482	290	186	::::	39
Mirrabooka 305	393971	6481639	45	489	--	--	--	463	263	201	::::	49
Mirrabooka 345	398053	6481679	46	529	--	--	--	510	306	209	::::	47
Mirrabooka 55	398039	6476132	32	500	--	--	--	--	304	208	::::	35
Moondah Brook	399706	6532768	98	134	--	--	--	--	63	47	::::	::::
Mounts Bay 2	390249	6462749	3	709	--	536	446	409	::::	::::	232	*
Mt Yokine 1	392279	6470429	24	912	740	559	476	441	250	195	::::	33
Mt Yokine 2	392399	6469189	14	762	749	560	477	440	257	201	::::	34
Multiplex 3	405339	6482437	23	257	573	466	439	354	236	143	::::	13
N. Gnangara DoW 01	384960	6528305	61	310	153	139	139	131	54	54	::::	54
N. Gnangara DoW 02	380732	6532667	54	139	--	--	--	--	45	44	::::	44
N. Gnangara DoW 03	386236	6523440	67	251	53	53	53	53	53	53	::::	53
N. Gnangara DoW 04	383210	6525932	60	306	198	145	145	138	50	50	::::	50
N. Gnangara DoW 05	382175	6530753	56	306	195	141	141	132	45	45	::::	45
N. Gnangara DoW 06	385370	6533226	56	335	235	186	186	161	49	49	::::	49
N. Gnangara DoW 08	384532	6521293	66	299	196	161	140	130	49	49	::::	49
N. Gnangara DoW 09	389012	6524542	69	305	48	48	48	48	48	48	::::	48
N. Gnangara DoW 10	386308	6519318	69	311	194	153	153	144	55	55	::::	55
N. Gnangara DoW 12	376450	6534029	40	109	--	--	--	--	38	38	::::	38
N. Gnangara DoW 13	383030	6534957	50	179	--	--	--	--	41	41	::::	41
N. Gnangara DoW 14	379510	6530559	50	311	262	180	180	170	50	50	::::	50

-- Surface depth below base of well, :::: Surface depth equal to overlying surface or ground,
* Surface present, depth not interpreted, Co-ordinate system: Geocentric Datum of Australia Zone 50

Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	**Surface (m below ground)**	Valanginian Unconformity	Base Kws	Base Kwlm	Base Kwlw	Base Kwlp	Aptian Unconformity	Paleocene Unconformity	Quaternary Unconformity
Pinjar 105	387193	6506015	71	198		--	196	185	177	75	75	::::	75
Pinjar 145	387271	6509806	78	206		--	204	192	186	76	76	::::	76
Pinjar 17	389998	6496339	57	589		461	365	311	248	80	58	::::	58
Pinjar 25	389408	6498296	58	220		--	--	--	--	60	60	::::	60
Pinjar 65	387787	6501978	55	150		--	--	--	--	59	59	::::	59
Pinjar 97	387239	6504749	58	400		--	--	--	--	61	61	::::	61
Pinjar Line 1	400370	6497050	67	346		--	--	--	--	175	175	::::	62
Pinjar Line 2	395490	6496630	75	657		572	395	355	311	131	94	::::	72
Pinjar Line 3	390060	6496400	58	541		450	360	306	242	75	58	::::	58
Pinjar Line 4	384780	6496560	72	518		377	377	298	239	84	84	::::	84
Pinjar Line 5	380590	6495320	42	496		315	315	233	185	63	63	::::	63
Pinjar Line 6	376640	6494110	10	610		341	341	247	191	39	39	::::	39
Pinjar State Elec. Co. 2	387749	6507967	70	222		225	218	207	197	71	71	::::	71
Polich J 2	400639	6527649	100	267		--	--	--	--	122	75	::::	::::
Q37	381075	6491181	17	990		847	790	474	410	114	96	::::	45
QA25	377613	6495588	25	221		--	--	--	182	63	63	::::	63
QO25	381036	6491169	18	204		--	--	--	--	117	100	::::	45
QZ35	376112	6498639	31	238		--	--	--	213	72	72	::::	72
Sandy Beach Reserve	400687	6467767	3	201		797	656	556	517	318	139	::::	7
Sir James Mitchell 3	384889	6461599	9	322		--	--	--	--	205	205	185	21
Tee Tree Downs	400789	6527699	95	180		--	--	--	--	122	75	::::	::::
WACA 2	394219	6463507	2	308		--	--	--	--	--	--	284	*
Wanneroo 1	387603	6486020	91	906		904	858	588	526	299	248	::::	112
Wanneroo 2	387614	6487006	89	280		--	--	--	--	276	221	::::	105
Wanneroo 25	395302	6487035	59	304		--	--	--	--	230	163	::::	59
Wanneroo 255	391059	6489599	55	450		--	--	--	435	256	172	::::	62
Wanneroo 257	391514	6489660	55	1109		913	815	531	435	247	171	::::	75
Wanneroo 275	391039	6491449	56	353		--	--	--	--	233	160	::::	60
Wanneroo 3	388431	6486569	63	304		--	--	--	--	257	223	::::	94
Wanneroo 55	394939	6489949	60	353		--	--	--	--	204	167	::::	60
Wanneroo 57	395058	6489798	59	1013		635	464	406	361	210	167	::::	62
Wanneroo 85	393265	6492184	62	304		--	--	--	--	157	110	::::	60
Wanneroo Reservoir 1	388431	6486569	87	302		--	--	--	--	257	224	::::	106
WC N. Gnagnara 5	383016	6516493	57	303		189	164	155	144	53	53	::::	53
WC N. Gnagnara 6A	386417	6521311	66	303		183	139	139	126	38	38	::::	38
WC N. Gnagnara 8	390416	6528092	66	297		50	50	50	50	50	50	::::	50
Woodridge 1 82	365439	6532549	38	292		--	--	--	--	209	209	::::	77
WT15	381999	6488239	59	256		--	--	--	--	153	137	::::	86
WT45	382924	6481907	32	275		--	--	278	237	84	84	::::	58
WT95	383729	6479652	45	281		--	--	--	256	105	105	::::	*
WT97	383757	6479704	50	440		434	360	299	256	105	105	::::	80
Yegan Park 1	398939	6537149	125	303		--	--	--	--	69	24	::::	*
Zoological 1	391909	6461629	20	642		--	585	489	451	::::	::::	314	*

-- Surface depth below base of well, :::: Surface depth equal to overlying surface or ground,
* Surface present, depth not interpreted, Co-ordinate system: Geocentric Datum of Australia Zone 50

Appendix C — Borehole data

Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	Downhole gamma-ray log	Downhole resstivity log	Palynology report
AM01	356924	6531829	53	793	✓	✓	✓
AM02	365646	6529649	36	881	✓		
AM02A	365659	6529664	37	515	✓		✓
AM03	367173	6535521	27	729	✓		✓
AM04	383790	6535459	50	549	✓	✓	✓
AM04A	383765	6535457	50	549	✓	✓	✓
AM05	375480	6527971	52	302	✓	✓	✓
AM06	386985	6529614	64	300	✓		✓
AM07	398727	6527718	102	718	✓	✓	✓
AM08	368988	6522790	52	809	✓	✓	✓
AM09	380917	6522375	59	303	✓	✓	✓
AM10	392249	6521848	69	298	✓	✓	✓
AM11	406614	6525106	190	810	✓	✓	✓
AM12	368581	6511653	16	838	✓	✓	
AM13	374909	6516946	54	798	✓	✓	
AM14	386758	6516658	75	810	✓	✓	
AM15	400874	6517429	69	784	✓	✓	
AM17	384288	6510078	72	301	✓	✓	✓
AM18	397130	6510141	77	300	✓	✓	✓
AM18A	399959	6510643	60	678	✓	✓	✓
AM19	405304	6507016	69	802	✓	✓	✓
AM20	377567	6500435	29	467	✓	✓	✓
AM21	387307	6503748	59	464	✓	✓	✓
AM22	395222	6501479	82	589	✓	✓	
AM23	380419	6493089	29	420	✓	✓	✓
AM24	389763	6491300	50	908	✓	✓	✓
AM25	396157	6494906	73	605	✓	✓	✓
AM26	404955	6497166	37	673	✓	✓	✓
AM26A	404909	6497609	38	366	✓		
AM26B	404929	6497309	37	374	✓		
AM26E	404909	6497207	37	249	✓	✓	✓
AM27	384680	6483682	34	762	✓	✓	✓
AM28	392620	6485039	53	624	✓	✓	✓
AM29	402291	6491061	48	758	✓	✓	✓
AM30	402431	6482066	50	747	✓	✓	
AM30Z	397699	6478981	39	555	✓	✓	✓

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Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	Downhole gamma-ray log	Downhole resistivity log	Palynology report
AM31	406171	6480712	6	800	✓	✓	
AM31A	406168	6480700	6	211	✓	✓	
AM32	383037	6473764	13	404	✓		
AM33A	385155	6477330	7	533	✓	✓	✓
AM34A	394664	6474341	41	734	✓	✓	✓
AM35A	403601	6475592	17	649	✓	✓	✓
AM36	387766	6470299	16	616	✓	✓	✓
AM37A	398469	6469322	21	1000	✓	✓	✓
AM38	404509	6468849	11	244	✓	✓	
AM38A	404921	6468931	11	551	✓		✓
AM40	394744	6460282	23	740	✓	✓	✓
AM41	404135	6460863	21	504	✓	✓	✓
Albert St	388989	6472389	18	741	✓		
Amelia St	387279	6473049	17	297	✓	✓	
Avon Valley	398039	6527349	120	231	✓	✓	
Badaminna (deep oil)	373216	6531740	37	2438	✓	✓	✓
Balcatta 2	388699	6471229	16	732	✓		✓
Barragoon (deep oil)	365500	6529515	40	2335	✓	✓	✓
Baskerville Oval 1	406814	6481906	22	229	✓	✓	
Beenyup 1/07	384261	6482827	21	345	✓	✓	✓
Bold Park 1	383919	6467519	13	763	✓		✓
Bold Park 2	384309	6466369	28	779	✓		✓
Bullsbrook (deep oil)	389922	6516851	91	4257	✓	✓	
Claremont Asylum 2	384800	6463145	30	642	✓		✓
Craige Production	384286	6481660	19	804	✓	✓	
Cullalla 1	406858	6538132	179	800	✓	✓	
Eclipse 1 (deep oil)	393254	6521877	78	3660	✓	✓	
G17	383598	6474795	28	945	✓	✓	
G27	383561	6469361	5	750	✓	✓	
G7	386820	6473223	12	745	✓	✓	
Gingin 1/75	396339	6532249	115	275	✓	✓	
Gingin Ashby	398539	6528649	115	189	✓		
Gingin Brook No 1	401258	6530836	117	544	✓	✓	✓
Gingin Brook No 2	386834	6534270	58	913	✓	✓	✓
Gingin Brook No 3	375859	6535424	31	729	✓	✓	✓
Gingin Brook No 4	361828	6534062	10	536	✓	✓	✓
Gingin Brook No 5	395400	6533465	104	516	✓	✓	✓

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Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	Downhole gamma-ray log	Downhole resstivity log	Palynology report
Gwelup 10	387191	6475035	17	363	✓		
Gwelup 125/87	389017	6472328	18	214	✓		
Gwelup 135	388759	6471189	23	305	✓	✓	
Gwelup 15	387189	6475029	16	305	✓	✓	
Gwelup 55	387147	6473813	13	302	✓	✓	
Gwelup 65	386819	6473279	14	248	✓		
Hector St	388398	6469562	16	225	✓		
Houghtons 2	406409	6474949	14	205	✓	✓	
Lambert 1/81	403939	6508849	60	267	✓		
Leederville 5	391166	6465067	16	942	✓	✓	
Leederville 6	390590	6465677	15	695	✓	✓	
Lexia 52	402970	6485078	44	247	✓		✓
Lilac Hill 2	402742	6470949	3	200	✓	✓	
Loftus St 1	390739	6465649	17	578	✓		
Loftus St 2	390739	6465649	17	625	✓		
McKechnie 1	401021	6531105	119	270	✓	✓	
Midland 1	407490	6467213	35	355	✓	✓	✓
Mirrabooka 1	393720	6476397	42	716	✓	✓	✓
Mirrabooka 115	395669	6477989	38	391	✓	✓	
Mirrabooka 15	393605	6476120	35	402	✓	✓	
Mirrabooka 2	393056	6476728	87	832	✓	✓	✓
Mirrabooka 285	402314	6479810	35	527	✓	✓	✓
Mirrabooka 305	393971	6481639	45	489	✓	✓	✓
Mirrabooka 345	398053	6481679	46	529	✓	✓	✓
Mirrabooka 55	398039	6476132	32	500	✓	✓	✓
Moondah Brook	399706	6532768	98	134	✓		
Mounts Bay 2	390249	6462749	3	709	✓		
Mt Yokine 1	392279	6470429	24	912	✓	✓	✓
Mt Yokine 2	392399	6469189	14	762	✓	✓	✓
Multiplex 3	405339	6482437	23	257	✓		
N. Gnangara DoW 01	384960	6528305	61	310	✓	✓	✓
N. Gnangara DoW 02	380732	6532667	54	139	✓	✓	✓
N. Gnangara DoW 03	386236	6523440	67	251	✓		✓
N. Gnangara DoW 04	383210	6525932	60	306	✓	✓	✓
N. Gnangara DoW 05	382175	6530753	56	306	✓	✓	✓
N. Gnangara DoW 06	385370	6533226	56	335	✓	✓	✓
N. Gnangara DoW 08	384532	6521293	66	299	✓	✓	✓
N. Gnangara DoW 09	389012	6524542	69	305	✓		✓
N. Gnangara DoW 10	386308	6519318	69	311	✓	✓	✓
N. Gnangara DoW 12	376450	6534029	40	109	✓	✓	✓
N. Gnangara DoW 13	383030	6534957	50	179	✓	✓	✓
N. Gnangara DoW 14	379510	6530559	50	311	✓	✓	✓

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Well	Easting	Northing	Ground (mAHD)	Base well (m below ground)	Downhole gamma-ray log	Downhole resstivity log	Palynology report
Pinjar 105	387193	6506015	71	198	✓	✓	
Pinjar 145	387271	6509806	78	206	✓	✓	
Pinjar 17	389998	6496339	57	589	✓	✓	
Pinjar 25	389408	6498296	58	220	✓	✓	
Pinjar 65	387787	6501978	55	150	✓	✓	
Pinjar 97	387239	6504749	58	400	✓	✓	
Pinjar Line 1	400370	6497050	67	346	✓	✓	✓
Pinjar Line 2	395490	6496630	75	657	✓	✓	✓
Pinjar Line 3	390060	6496400	58	541	✓	✓	✓
Pinjar Line 4	384780	6496560	72	518	✓	✓	✓
Pinjar Line 5	380590	6495320	42	496	✓	✓	✓
Pinjar Line 6	376640	6494110	10	610	✓	✓	✓
Pinjar State Elec. Co. 2	387749	6507967	70	222	✓	✓	
Polich J 2	400639	6527649	100	267	✓	✓	
Q37	381075	6491181	17	990	✓	✓	✓
QA25	377613	6495588	25	221	✓	✓	
QO25	381036	6491169	18	204	✓	✓	
QZ35	376112	6498639	31	238	✓	✓	
Sandy Beach Reserve	400687	6467767	3	201	✓	✓	
Sir James Mitchell 3	384889	6461599	9	322	✓	✓	✓
Tee Tree Downs	400789	6527699	95	180	✓		
WACA 2	394219	6463507	2	308	✓		✓
Wanneroo 1	387603	6486020	91	906	✓	✓	✓
Wanneroo 2	387614	6487006	89	280	✓		
Wanneroo 25	395302	6487035	59	304	✓	✓	
Wanneroo 255	391059	6489599	55	450	✓	✓	
Wanneroo 257	391514	6489660	55	1109	✓	✓	
Wanneroo 275	391039	6491449	56	353	✓	✓	
Wanneroo 3	388431	6486569	63	304	✓		
Wanneroo 55	394939	6489949	60	353	✓	✓	
Wanneroo 57	395058	6489798	59	1013	✓	✓	
Wanneroo 85	393265	6492184	62	304	✓		✓
Wanneroo Reservoir 1	388431	6486569	87	302	✓	✓	✓
WC N. Gnagnara 5	383016	6516493	57	303	✓	✓	
WC N. Gnagnara 6A	386417	6521311	66	303	✓	✓	
WC N. Gnagnara 8	390416	6528092	66	297	✓		
Woodridge 1 82	365439	6532549	38	292	✓	✓	
WT15	381999	6488239	59	256	✓	✓	
WT45	382924	6481907	32	275	✓	✓	
WT95	383729	6479652	45	281	✓	✓	
WT97	383757	6479704	50	440	✓	✓	
Yegan Park 1	398939	6537149	125	303	✓	✓	
Zoological 1	391909	6461629	20	642	✓		✓

AM: Department of Water Artesian Monitoring Bore,
DoW: Department of Water, WC - Water Corporation

Shortened forms

AHD	Australian height datum
FA	Facies association
IWSS	Integrated Water Supply Scheme
kyr	Kilo year (thousands of years)
Ma	Millions of years ago
PRAMS	Perth regional aquifer modelling system

Glossary

Abstraction The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.

Aeolian strata Sediment deposited by the wind.

Aggradation The vertical accumulation of sediments.

Antithetic fault A minor, secondary fault, usually one of a set, whose sense of displacement is opposite to its associated major and synthetic faults.

Aptian An age in the Early Cretaceous epoch from 125 to 112 million years ago.

Aquiclude Rock interval with very low hydraulic conductivity.

Aquifer Permeable rock interval able to receive, store and/or transmit large amounts of water.

Aquitard Rock interval with moderately low hydraulic conductivity.

Archean Geological eon from 2.5 to 3.8 billion years ago.

Barremian An age in the Early Cretaceous epoch from 130 to 125 million years ago.

Biostratigraphy Branch of stratigraphy which focuses on correlating and assigning relative ages of rock strata by using the fossil assemblages contained within them.

Bioturbation The mixing and displacement of sediment by animals and plants.

Chronostratigraphy Branch of stratigraphy that studies the age of rock strata in relation to time.

Clast Sediment grain.

Coeval Originating or existing during the same period.

Confined aquifer Saturated, permeable rock interval lying between an upper and lower interval of low permeability, where the hydraulic head is higher than the upper surface of the aquifer.

Craton An old and stable part of the continental lithosphere.

Cretaceous	A geological period 145 to 65 million years ago.
Delta front	The sloping portion of a delta that develops seaward of the delta plain.
Delta plain	The flat, landward portion of a delta, composed of distributary channels and interdistributary bays.
Depocentre	The site of maximum deposition within a sedimentary basin, where the thickest sedimentary sequence will be found.
Detritus	Loose rock or minerals that originated from weathering of older rocks.
Diagenesis	Chemical or physical change undergone by a sediment after its initial deposition and during its lithification.
Disconformity	An unconformity between parallel layers of rocks that represents a period of erosion or non-deposition.
Distributary	A channel that branches off and flows away from the main river channel, common in deltas.
Downhole	Occurring in the drilled borehole.
Drawdown	The difference between the elevation of the initial piezometric surface, and its position after pumping or drainage.
Facies	A distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular process or environment.
Flaser bedding	Sedimentary bedding created during intermittent flow conditions, leading to sand-rich ripples with isolated mud drapes.
Fluvio-	Referring to rivers and streams.
Formation resistivity factor	A measure of the contribution of the sediment to the overall formation resistivity.
Geostatistics	A branch of statistics focusing on spatial datasets.
Glauconite	An iron potassium phyllosilicate mineral of characteristic green colour, generally considered a diagnostic mineral indicative of marine depositional environments.
Gondwana	Southern hemisphere supercontinent from 510 to 180 million years ago.

Groundwater	Water that occupies the pores with a rock or soil profile.
Groundwater discharge	Water that leaves an aquifer, either at the surface, or into another aquifer.
Groundwater recharge	Water that infiltrates into an aquifer.
Hauterivian	An age in the Early Cretaceous epoch from 136 to 130 million years ago.
Heterogeneous	Composed of diverse, dissimilar parts.
Heterolithic	Heterogeneous sediments, e.g. composed of intervals of both sand and mud.
Hydraulic conductivity	Ease with which water is conducted through an aquifer.
Hydraulic gradient	The rate of change of hydraulic head per unit distance, at a given point and in a given direction.
Hydraulic head	The height of a free surface of a body of water above a given subsurface point.
Ichnology	The study of trace fossils.
Interdistributary bay	Flood plain, tidal flat or swamp that lies between distributaries.
Intertidal	Between low and high tide.
Isopach	A contour that connects points of equal thickness.
Isopotential	A contour that connects points of equal hydraulic head, or head difference.
Kriging	A geostatistical technique to interpolate the value of a random field at an unobserved location from observations of its value at nearby locations.
Lenticular bedding	Sedimentary bedding created during intermittent flow conditions, leading to laterally discontinuous sand-rich ripples within mud layers.
Levees	An elongated ridge bounding a river channel.
Listric fault	A type of fault in which the fault plane is curved. The dip of the fault plane becomes shallower with increased depth.
Lithology	A description of the physical characteristics of a rock unit.

Lithosphere	The crust and upper mantle of the earth.
Lithostratigraphy	A branch of stratigraphy that focuses on the physical characteristics of rocks.
Mesotidal	With a moderate tidal range.
Microplankton	Microscopic, drifting organisms that inhabit the open water, or pelagic zone, of ocean, sea or fresh water.
Miospore	A collective term for microspores and pollen grains.
Neocomian	An historical term for the earliest Cretaceous, comprising the Berriasian, Valanginian, Hauterivian and Aptian ages.
Orogen	Tracts of deformed rock formed during a mountain building period.
Paleocene	A geologic epoch from 65.5 to 56 million years ago.
Paleoecology	Ecosystems of the past.
Paleoenvironment	The past environment of an area for given period in its history.
Paleorecharge	Groundwater recharge of the past.
Palynology	The study of organic microscopic objects.
Palynomorph	A microscopic particle composed of organic material.
Penecontemporaneous	Formed during or slightly after deposition of the host rock.
Petrography	Study based on the detailed description of rocks.
Petrophysics	Study of the physical and chemical properties that describe the occurrence and behaviour of rocks.
Potentiometric or piezometric surface	Surface describing the distribution of hydraulic head in an aquifer.
Precambrian	Geological supereon that spans from the creation of the Earth 4.6 billion years ago to 542 million years ago.
Prograde	Deposition of sediment progressively further out into a basin.
Proterozoic	Geological eon from 2,500 to 542 million years ago (Ma).
Salinity	A measure of the total solids dissolved in water.

Sedimentology The study of sediments and the processes that result in their deposition.

Sequence stratigraphy A branch of stratigraphy that focuses on the correlation of surfaces that represent times or events, placing strata in a chronostratigraphic framework that describes the changing depositional conditions.

Shoreface Sloped, coastal portion of the sea bed that is affected by the action of waves.

Siliciclastic Clastic, silica-bearing sedimentary rocks.

Stratigraphy Study of the history, composition, relative ages and distribution of strata to elucidate the Earth’s history.

Subaerial Exposed at the Earth’s surface.

Subcrop To lie directly beneath another geological unit.

Subtidal Being below low tide.

Syn-depositional Occurred during deposition.

Syn-rift Occurred during rifting.

Synthetic fault A type of minor fault whose sense of displacement is similar to its associated major fault.

Terrestrial Being of land origin.

Transtensional Experiencing both extensive and transtensive (lateral) shear.

Unconfined aquifer A permeable rock interval only partly filled with water, overlying a relatively impermeable layer, its upper boundary formed by a free watertable under atmospheric pressure.

Unconformity A surface separating strata of different ages, representing a period of erosion or non-deposition.

UWA University of Western Australia

Valanginian An age in the Early Cretaceous epoch from 140 to 136 million years ago.

Watertable The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

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