Australian Government
National Water Commission
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Palaeovalley Groundwater Resources in Arid and Semi-Arid Australia

A Literature Review

John Magee

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by

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Cover Image: A chain of salt lakes defines the trend of this Western Australian palaeovalley system. This oblique aerial photograph was provided by Phil Commander and used with his express permission.

Executive Summary

INTRODUCTION

Palaeodrainage networks are present over much of arid Australia with their prolonged preservation reflecting the continent's long-term tectonic stability, relatively low relief and the geologically slow rates of erosion and sedimentation. Although the palaeovalleys no longer function as surficial fluvial systems they are active elements of the landscape and represent dynamic groundwater systems. The modern morphologic and landscape expression of the palaeovalleys reflects interaction between their stratigraphic record, ongoing Quaternary depositional processes and climatic effects, and the evolution of groundwater salinity, particularly in the topographically lower parts of the valleys. The existence, size and nature of palaeovalley playas or salt lakes are directly controlled by their role as discharge points for palaeovalley groundwaters and the evolution of groundwater salinity. Less saline groundwater can occur beneath up-catchment reaches and interfluves in the palaeodrainage systems.

ANTIQUITY OF PALAEOVALLEYS

The palaeodrainage networks are mostly pre-Cenozoic in origin, with some Cambrian-aged valleys recognised in the North Australian Craton. Over most of arid Australia, Permian continental glaciation removed or strongly modified much of the pre-existing landscape. Some sub-glacial tunnel valleys were formed but remnant in-valley Permian glacial sediments are likely to be buried and little has been identified. The fundamental physiography and palaeodrainage setting for arid Australia was established during the Mesozoic. Networks of wide, shallow precursor palaeovalleys with no sedimentary infill existed at the end of the Cretaceous when Australia rifted from Antarctica and began its northward drift. Epeirogenic uplift in the Palaeocene to Early Eocene, as an adjustment to rifting, initiated incision of inset-valleys within the Mesozoic precursor or primary valleys. After incision and deposition of Late Eocene channel sands, deep weathering occurred with weathering greatest adjacent to the palaeochannel sands where it was facilitated by groundwater circulation. The widespread palaeodrainage networks of palaeovalleys that we see in the arid landscape today are the remnant Early Cenozoic inset valleys with an Early to Middle Tertiary sedimentary infill and a thin, variable, and pervasive Quaternary cover.

STRATIGRAPHIC ARCHITECTURE AND THE CHRONOLOGICAL AND PALAEOENVIRONMENTAL EVOLUTION OF PALAEOVALLEYS

In most cases the age of palaeovalley sequences is determined by palynology. This leads to widespread uncertainties due to poor pollen preservation (common) and uncertain correlations to the only continuous and relatively well-studied Cenozoic palynological record on the continent – the Gippsland Basin. However, despite these uncertainties, the composition of Tertiary palaeovalley infill is remarkably uniform across the continent. It generally consists of a two-part stratigraphic sequence consisting of Early Tertiary fluvial sand overlain by Mid Tertiary, fine-grained sediments which formed in a lower-energy environment, e.g., under lacustrine conditions.

The basal unit is dominated by high-energy fluvial sands which mainly formed in braided river environments under wet climatic conditions characterised by widespread mesothermal and megathermal rainforests. Basal gravels are widespread and sands are very commonly carbonaceous with lignites and finer-grained interbeds representing swamp and valley lacustrine deposits. Plant macro fossils (wood and leaves) and pollen are abundant and relatively well preserved; a Mid to Upper Eocene age for this facies has been established for most of the continent. The basal gravels and sands function as important aquifers in active palaeovalley groundwater systems. In southern

Australia, particularly the Eucla Basin margins, the relatively high-level eustatic marine transgressions of the Middle and Late Eocene inundated near-coastal reaches of the palaeovalleys. This resulted in deposition of estuarine and marine sediments that inter-finger with fluvial deposits in many palaeovalleys. On the western margin of the Eucla Basin, the eastern Yilgarn has been epeirogenically uplifted since the Eocene and marine-influenced deposits are now found to almost 300 metres Australian Height Datum (AHD).

The upper stratigraphic palaeovalley unit unconformably overlies the lower sand-rich unit and is more complex lithologically and mineralogically. It is dominantly fine-grained and was deposited in low-energy, mostly lacustrine environments. Clays are abundant and some are authigenic (palygorskites); carbonates (dolomitic clay and dolomite) are also common. Depositional environments are interpreted as valley lakes and wetlands with climates drier than during the Eocene fluvial deposition. Pollen is generally poorly preserved in the upper unit and its chronological age is consequently poorly constrained. It is unconformable on the lower unit and clearly represents deposition in a markedly different climatic and hydrologic regime. The upper unit is widely interpreted as representing deposition in the Late Oligocene to Mid Miocene, and minor pollen, plant macro-fossil and vertebrate fossil evidence supports that correlation. In the various Yilgarn palaeovalleys the upper unit has long been interpreted as conformable with the lower unit and accordingly assigned an Upper Eocene age. This apparent dichotomy with all other palaeovalley sequences requires resolution for a realistic Australia-wide understanding of palaeovalley evolution. It seems intuitively unlikely that the western Eucla Basin (eastern Yilgarn) tributary palaeovalleys will have a markedly different sedimentary sequence to the eastern Eucla Basin margin palaeovalleys. One interpretation could be that the dichotomy is real and reflects genuine differences in post-Eocene depositional history due to post-Eocene epeirogenic uplift of the Yilgarn. However, more recent detailed stratigraphic analysis of the eastern Yilgarn palaeovalley sequences, in open-pit mine exposures, has demonstrated that the upper unit unconformably overlies the lower unit and contains some poorly preserved pollen indicative of an Oligo-Miocene age. This suggests that the earlier, widely held interpretation of an Upper Eocene age is erroneous. Recent analysis of the western Yilgarn Beaufort palaeovalley sequence where an upper fine-grained lacustrine unit contains Upper Eocene pollen adds further complexity to this issue and suggests that stratigraphic clarification is required. Only the lowest reaches of the most south-eastern Eucla Basin margin palaeovalleys were affected by marine conditions during Miocene and Pliocene eustatic sea-level transgressions.

Cenozoic palaeovalley fill generally overlies deeply weathered basement rocks and the palaeovalley sediments themselves are commonly affected by secondary processes. Both of the palaeovalley units described above, and the unconformable boundary between them, have been affected by deep weathering processes and the deposition of secondary duricrust materials. Ferricrete, silcrete and calcrete occur in various forms and abundances depending on local or regional conditions.

Minor fine-grained lacustrine sedimentation, similar in style to the Oligo-Miocene sequence, is attributed to the Pliocene in some palaeovalleys. For example, at Yenyenning in the Yilgarn/Salt River palaeovalley (Western Australia) a considerable thickness of Pliocene lacustrine sediments was deposited in response to the local tectonic setting. Overall however, relatively little palaeovalley sedimentation has occurred since the Oligo-Miocene. In the Quaternary, widespread but thin colluvial, alluvial and aeolian sediments have blanketed much of the arid zone landscape including the palaeovalleys. In most areas this surficial mantle is not sufficient to completely obscure the underlying palaeodrainage topography except where relatively thick aeolian dunefield accumulations occur, such as in the Great Sandy Desert, Great Victoria Desert and Simpson Desert.

The palaeovalleys are now defunct as fluvial systems and are obscured by thin surficial sediment cover however they are still actively evolving landscape elements. Evaporation from playas and salt lakes represents substantial discharge from the palaeovalley groundwater systems and results in increased groundwater salinity especially in the near-playa environment. Fresher groundwater is common away from these playa discharge zones in many regions. Disruption of playa sediment by crystallising salts, salt weathering of surrounding rocks and sediments and deflation of materials under uni-directional winds can result in enlargement or migration of playas, deposition of lunettes and dunes and generation of salt-rich dust. The playas are manifestations of the interaction of Quaternary groundwater, regolith and climatic processes, rather than being dismembered elements of former channels.

Australia's arid zone palaeovalleys are dominantly incised into bedrock terranes, especially those of Archaean and Proterozoic age which contain relatively abundant economic mineral deposits. The palaeovalleys themselves can contain useful indicators of the location of primary mineralisation or act as sites of secondary concentrations of economic significance. These can be in the form of metal or precious stone placers, secondary supergene enrichment or as secondary replacement and deposition from solution at redox boundaries (such as in uranium roll-front deposits). The combination of potential mineral deposits and groundwater reserves has thus made palaeovalleys a high-value and prospective resource target in many regions. They are increasingly sought and mapped by sophisticated geophysical and remote sensing techniques and their subsurface sedimentary architecture investigated by drilling.

PALAEOVALLEY GROUNDWATER SYSTEMS

Although palaeovalleys are defunct fluvial systems now filled with early, middle and late Cenozoic sediments, they remain active groundwater systems which have evolved during the alternate cool-dry /warm-wet, glacial/interglacial climate cycles of the Quaternary. Recharge has been episodic and most effective during warm-wet, interglacial periods and discharge has been dominant during the dry phases by means of evaporation through playas and salt lakes. The basal Middle to Later Eocene fluvial sand unit is generally a continuous aquifer at regional scales and has considerably greater storage potential and transmissivity than adjacent fractured or weathered basement rocks. The basal sand aquifer is generally contained within the deeply incised portion of the palaeovalley and is confined above by the overlying fine-grained Oligo-Miocene lacustrine sediments. The latter usually extends laterally beyond the basal sand aquifer to directly overlie weathered basement at the upper palaeovalley margins. Thus, broad-scale lateral connectivity of the basal sand aquifer is restricted to surrounding weathered bedrock and the sand aquifer of tributary valleys within given palaeodrainage networks. Recharge occurs from:

- Direct exposure of the aquifer to rainfall by various mechanisms, especially where the overlying lacustrine unit is absent (particularly in upper reaches of the palaeodrainage network);
- Up-gradient aquifers in tributary valleys; and
- Weathered bedrock aquifers (especially where fractured rocks are present in the basement).

However, despite these temporal and stratigraphic constraints on potential recharge, previous studies have shown that some unexploited palaeochannel sand aquifers (e.g., in Wester Australia's Yilgarn region) are effectively full at present, and cannot accept additional recharge. A similar situation may exist for palaeovalleys in other regions.

Palaeovalley aquifers typically have a higher storage capacity and hydraulic conductivity than adjacent and more extensive weathered and fractured basement aquifers, and bores can yield relatively significant quantities of water. Cross-sectional areas of palaeovalley aquifers are limited by their relatively shallow depth (typically < 50 m) and narrow widths (typically 100's to 1,000's of metres), but they can extend for great distances longitudinally down-valley (typically 10's to 100's of kilometres), with good aquifer connectivity along the length of the palaeovalley. Thus palaeovalley aquifers represent an extremely valuable storage reserve where extraction is effectively limited not only by the size of the reservoir aquifer but by the ability of down-valley hydraulic conductivity to replenish reserves. In some palaeovalleys where lateral and vertical confinement is very effective, bore drawdown is rapid and significant and recovery is slow. In other palaeovalleys, the speed of drawdown recovery is substantially more rapid, presumably due to enhanced lateral inflow from adjacent bedrock aquifers. Where lateral inflow from weathered bedrock aquifers occurs in response to extraction, the volume of groundwater in the palaeovalley aquifer may significantly increase as the bedrock systems are far more extensive than the palaeovalley aquifers, even though they have a lower holding capacity per unit area.

Palaeovalley groundwater quality is commonly poor and often does not fall within safe limits for human consumption. It generally exceeds both human and stock water drinking limits for salinity or toxic elements such as nitrates, sulfates, fluoride and in some cases for radionuclides. The high salinities have evolved as a consequence of playa evaporation dominating discharge from the groundwater systems. It seems probable, therefore, that palaeovalleys marked by few and/or small playas are likely to have less evolved (lower) salinities. Salinity levels tend to increase down-valley and there may be opportunities for community water supplies from the upper reaches of some palaeovalleys, or in the lower reaches where the palaeovalleys flow to the coast and may receive greater rainfall and higher rates of recharge and throughflow.

In Cenozoic basins near upland ranges in central Australia palaeovalleys commonly contain the freshest – often potable – groundwater reserves within catchments, whereas adjacent palaeo-interfluve aquifers contain more saline groundwater. In these settings where episodic recharge occurs in the contemporary climate regime, the palaeovalleys are the main conduits for recharge waters derived from bedrock ranges runoff and overland flow, and only in their lowermost reaches do they function as discharge zones. In palaeovalley systems in the WA Wheatbelt there are small isolated segments of fresh groundwater, although saline to hypersaline groundwater is more typical where discharge occurs in broad flat areas. Perched fresh groundwater is also common in aeolian cover sediments within broad-scale palaeovalley regions.

In most cases however human consumption of palaeovalley groundwater resources will require desalination – this is currently expensive, though utilised in some mining communities and tourist centres (such as Yulara Resort, Uluru). Desalination for stock watering is unlikely to be economically viable except via shandying with lower-salinity surface water (runoff dams). However, desalination technology, particularly by reverse osmosis, is progressively improving and is becoming increasingly cost-competitive. Consequentially, palaeovalleys may represent viable water resources for various applications including remote communities, mining operations or horticultural activities in the future. Palaeovalley groundwater undoubtedly represents an attractive water resource for mineral processing. It is typically available in sufficient quantities, often accessible relatively close to remote mines and has the advantage of not being a usable or attractive resource to other consumers, i.e. when high salinity is not a negative factor for ore processing.

The discovery and recognition of arid zone palaeovalley systems has been greatly enhanced in recent decades by improved technologies, even in areas with pervasive and uniform surficial cover. In particular, improved topographic resolution through the use of digital elevation models (DEM) and airborne and spaceborne altimetry, combined with various geophysical methods and the application of Geographic Information Systems (GIS) has been used to identify and map palaeodrainage networks (including tributaries) in considerable detail. However, it is much less certain that the nature or even the location of the main palaeochannel facies, or the palaeovalley thalweg, within the broader palaeovalley context can be identified through remote techniques. Airborne geophysical methods, such as airborne electromagnetic (AEM) surveys, probably have the greatest potential to achieve such identification. The palaeovalley thalweg represents the thickest sequence of the lower fluvial sand aquifer; its recognition is a crucial step in characterising the most optimal groundwater resources within palaeovalley systems. Thalweg location reflects the unpredictable migration of Eocene river channel morphology and is not reflected in the architecture of either the overlying Oligo-Miocene lacustrine unit or the Quaternary deposits and playas. Previously, it has only been possible to recognise and map the location and morphological characteristics of palaeovalley aquifers, and obtain detailed information on aquifer and groundwater properties, by comprehensive drilling programs, e.g., cross-section transects.

RECOMMENDATIONS FOR THE PALAEOVALLEY GROUNDWATER PROJECT

The following recommendations arise from this literature review and are intended to provide a guide to new research directions that can answer clearly apparent uncertainties associated with the Raising National Water Standards (RNWS) project: ‘Water for Australia’s Arid Zone – Identifying and Assessing Australia’s Palaeovalley Groundwater Resources’ (referred to herein as the ‘Palaeovalley Groundwater Project). The recommendations are presented as non-exhaustive considerations and are not constrained to demonstration sites nominated in the project, but note is made where they coincide with those sites: the Tanami region (NT-WA); Gawler Craton – Eucla Basin (SA); Haast Bluff Aboriginal Land Trust (ALT) (NT); Willowra–Ti-Tree area (NT); the Paterson Province (WA); and the Gascoyne – Murchison region (WA).

Part A

The most intensively studied and best understood palaeovalleys, in terms of both the sedimentary architecture and groundwater resources, occur in the Yilgarn Province of Western Australia. Limited surficial cover and the widespread presence of playa lakes and other surface manifestations of palaeovalleys has facilitated regional-scale mapping of the palaeodrainage network. In addition, extensive drilling and groundwater testing has enabled detailed and reliable resolution in both the eastern and western Yilgarn palaeovalley systems. However, there is ongoing uncertainty as to whether the upper fine-grained lacustrine unit is Upper Eocene or Oligo-Miocene in age. While this chronological question has little impact on the groundwater properties therein, it is relevant to an improved understanding of the continent-wide evolution and for reconstruction of the distribution of palaeovalley systems.

Recommendation 1

It is recommended that the nature of the stratigraphic contact between the lower fluvial unit and the upper lacustrine unit be reassessed from a wide array of palaeovalleys, as has been conducted recently in the Roe Palaeovalley in the Yilgarn (de Broekert, 2002). Additionally, previously collected subsurface samples should be rigorously investigated for potential pollen preservation in the upper unit, and new samples obtained by drilling (where possible) and submitted for expert pollen-zone analysis.

Recommendation 2

Because the stratigraphic architecture and groundwater characteristics are best known from some of the Yilgarn palaeovalleys, and drillhole data is relatively plentiful, these should provide suitable test cases for further application of Geoscience Australia's (GA's) emerging capability in the field of 3D geologic modelling and conceptualisation for groundwater applications.

Recommendation 3

Sustained significant groundwater abstraction from the Roe Palaeovalley for mineral processing has occurred since the mid- to late-1980's and been systematically monitored for much of that time. Early studies suggested that enhanced lateral recharge from the surrounding weathered bedrock aquifer resulted from groundwater extraction, and thus implied a significant enhancement of the originally estimated groundwater reserves. Subsequent modelling and analyses suggested that this enhancement was insufficient to prevent depletion of groundwater storage as soon as sometime between 2012 and 2022. However, monitoring of water-level response to abstraction had demonstrated by the late-1990's that lateral indirect recharge (enhanced by abstraction) is sufficient to enable sustainable groundwater use and water-level recovery when abstraction is reduced. This finding in the Roe Palaeovalley is extremely important for understanding the limits to exploitation of palaeovalleys in all regions and should be further examined and quantified by numerical modelling. The application of GA's 3-D hydrogeologic modelling might also be useful to address this question.

Part B

The Eastern Eucla Basin palaeovalleys of the Gawler Craton (South Australia) are well-mapped, including the location of an extensive network of minor tributary systems, e.g., Primary Industries and Resources of South Australia, 2007. However, only limited palaeovalley drilling has occurred (in the Garford, Kingoonya and Narlaby palaeovalleys) and hence the subsurface stratigraphic architecture, and the characteristics of the contained groundwater resources, are poorly defined for other palaeovalleys. In general, there is a paucity of detailed information about the aquifer properties and the chemical composition of the groundwater in palaeovalleys from the Gawler Craton and Eucla Basin. This area is one of the nominated demonstration sites for the Palaeovalley Groundwater Project.

Recommendation 4

The Gawler Craton region is probably ideal for testing the ability of remote sensing or geophysical techniques, such as airborne electromagnetic (AEM) surveying, to elucidate subsurface palaeovalley structure and composition, and the groundwater characteristics. This should be achievable by obtaining and comparing datasets from the Garford and Kingoonya palaeovalleys (where considerable information exists from previous drilling transects) with adjacent palaeovalleys such as the Tallaringa system, where subsurface properties are likely to be identical, but where no drilling has occurred. The overall lack of groundwater information about Gawler Craton palaeovalleys should be addressed as part of this project. This will require detailed examination of unpublished information (most probably in South Australian Government records) and additional drilling transects combined with water bore pumping tests and groundwater chemical analyses.

Part C

The age and stratigraphic architecture of Central Australian ranges palaeovalley sequences are relatively poorly known. The depositional sequences probably match those in Cenozoic intermontane basins which have been comparatively well explored and exploited for groundwater resources, but which are also stratigraphically and chronologically poorly constrained.

Recommendation 5

The Central Australian palaeovalleys require enhanced knowledge of their stratigraphic sequences, chronological history and groundwater resources. The Haast Bluff ALT demonstration site for the

Palaeovalley Groundwater project is located in this region. Further studies involving analysis of remote sensing data and/or application of geophysical techniques (such as AEM) should be combined with new drilling transects, bore pumping tests and groundwater chemical analyses.

Part D

The location of Tanami region palaeovalleys is reasonably understood from recent regolith studies combined with remote sensing and geophysical techniques. They are less well-defined in terms of their subsurface architecture and groundwater resources, except in areas subject to extensive mineral exploration and mining.

Recommendation 6

Similar to the Gawler Craton the Tanami region is probably ideal for testing the ability of remote sensing or geophysical techniques (such as AEM) to elucidate the subsurface palaeovalley structure and composition, and possibly the groundwater characteristics. This should be achievable by comparing datasets from some of the well-constrained palaeovalleys in the Tanami with adjacent less well-known palaeovalley systems.

Part E

In general, other palaeovalley networks in arid Australia are poorly understood, including the Musgrave Ranges to Eucla Basin tributaries, the Eucla Basin tributaries in the Gibson Desert and Great Victoria Desert, the Officer Basin and eastward-trending Pilbara palaeovalleys of the Great Sandy Desert, the Canning Basin palaeovalleys of the Great Sandy Desert and the remote Lake MacKay system straddling the NT–WA border.

Recommendation 7

These remote and very poorly understood palaeovalley systems should be examined, probably later in the Palaeovalley Groundwater Project when opportunities present themselves and when effective exploration methodologies have evolved further. In many instances these palaeovalleys are characterised by few and small playa systems and it may be possible to find new potable water supplies for remote indigenous or mining communities. This will require application of remote sensing or geophysical techniques (such as AEM), drilling transects combined with bore pumping tests and groundwater chemical analyses. The Tanami, Haast Bluff, Musgrave and Paterson region demonstration sites are located in or partially overlap with these regions.

Part F

As detailed above, the palaeovalley groundwater systems are not Early to Mid Cenozoic relicts as are the palaeovalley sediments. Groundwater recharge has been and is controlled by Quaternary climate and landscape dynamics. As with all groundwater systems, there is considerable system-wide inertia, which leads to complexity when assessing attributes such as sustainable extraction rates. When major recharge episodes of perhaps 10,000 years occur episodically at 100,000 year intervals, sustainability assessment should not simply be a matter of comparing extraction rates to estimates of modern recharge. Knowledge of Quaternary palaeoclimatic history and landscape processes is essential to understanding groundwater evolution and processes in palaeovalleys, and to assess the sustainability of extraction.

Recommendation 8

The suggestion that palaeovalley groundwater salinity is lower in palaeovalleys with fewer and smaller playas should be investigated in detail. This investigation would require examination of the groundwater characteristics of areas representative of the four palaeovalley playa types recognised in

Section 2.8.1. Groundwater in palaeovalleys with abundant playas has already been investigated in detail whereas groundwater characteristics in palaeovalleys with relatively few playas are poorly understood. Selection of study areas to fill these knowledge gaps can probably be incorporated into the demonstration site studies.

Recommendation 9

The proportion of palaeovalley groundwater discharge which occurs through playas, versus volumes of throughflow along valleys located down-gradient from playas, should be investigated. Studies by Commander et al. (1992) and Turner et al., (1994) in the eastern Yilgarn suggested that playa discharge volumetrically dominates groundwater discharge, but this is not consistent with the observed paucity of significant highly soluble evaporite salts (especially halite) accumulating in these playas. Further investigation of playa discharge versus throughflow should be undertaken by on-site investigation and modelling in the Yilgarn and other sites.

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1. Introduction

1.1. BACKGROUND

This literature review represents Milestone 3 of the Raising National Water Standards (RNWS) project: *Water for Australia's arid zone – identifying and assessing Australia's palaeovalley groundwater resources*, hereafter referred to as the 'Palaeovalley Groundwater' Project[1]. The project aims to develop and deliver an innovative and integrated national strategy for defining the quantity, quality, dynamics and sustainability of groundwater in Australian palaeovalleys, focussing on the arid zone where other water sources are limited. The project aims to achieve this by improving knowledge of the extent and recharge of palaeovalley groundwater in seven demonstration sites across Western Australia, South Australia and the Northern Territory. This knowledge will be directed towards developing criteria for locating potable to low salinity groundwater resources in palaeovalley systems and to reach agreement on a national multi-disciplinary approach to delineating and managing palaeovalley groundwater resources. This literature review was initially conducted over a three month period in early-2007, financed by Geoscience Australia prior to award of funding for the four-year collaborative project. The investigation has subsequently been completed, after the award of National Water Commission funding, from mid-2008 to early-2009. The overall objective is to review existing literature on arid zone palaeovalleys and their groundwater resources, to help guide future research efforts undertaken as part of this project.

1.2. EXTENT OF STUDY

This literature review focuses on the following aspects:

- The stratigraphic and hydrogeologic characteristics of palaeovalleys in the Australian arid and semi-arid zones;
- Previous hydrogeological and geophysical investigations of palaeovalleys in the Australian arid and semi-arid zones, including:
  - o Implications for understanding the geologic and geomorphologic evolution of palaeovalley systems.
  - o Implications for understanding the hydrogeology of groundwater systems contained in palaeovalleys.
  - o The suitability and usefulness of geophysical exploration techniques used to locate and better understand palaeovalleys.
- International geophysical investigations of palaeovalley groundwater systems in other arid climates around the world, and their suitability or usefulness in the Australian context; and
- The relative advantages and disadvantages of geophysical and remote sending techniques for mapping and understanding palaeovalley groundwater systems in the arid zone in Australia.

It was agreed at the outset that it would not be possible to cover all aspects in equal detail and that the emphasis of the report would be on the stratigraphic, landscape and groundwater characteristics of palaeovalleys, due to the author's experience and expertise. This focus allows a higher level of synthesis of existing information and some incorporation of novel insights. At the same time, it was

[1] This project is funded through the National Water Commission, under the Raising National Water Standards program. The four-year project, which began on 1 April 2008, was initiated by Geoscience Australia and a consortium of state government water resource agencies and geological survey organisations.

agreed that all information regarding geophysical and remote sensing methods encountered during the research phase would also be summarised.

It was also intended that the report would have a wide focus on palaeovalleys throughout the arid and semi-arid regions of Australia, rather than focus exclusively on palaeovalley sequences from the project's following list of nominated demonstration sites:

- The **Tanami** region (Western Australia and the Northern Territory);
- The **Haast Bluff** Aboriginal Land Trust (Northern Territory);
- The **Willowra – Mount Barkly** area (Northern Territory);
- The **Gawler Craton – Eucla Basin** (South Australia);
- The **Gascoyne – Murchison** region (Western Australia);
- The **Musgrave Province** (South Australia, Northern Territory and Western Australia); and
- The **Paterson Province** – Canning Basin (Western Australia).

This approach provides a broader and more useful background document for the project. Additionally, the choice of demonstration sites was not considered as a final or binding limitation on the scope of the project, which is aimed at identifying and assessing Australia's arid zone palaeovalley groundwater resources nation-wide rather than within strictly defined study areas.

Finally, the scope of the literature review is delimited geographically by the specific focus of the Palaeovalley Groundwater Project on arid and semi-arid regions which lack other reliable water resources (Figure 1.1). Thus the deep-lead systems in Australia's Eastern Highlands, which are effectively palaeovalleys that host palaeochannel sediments that commonly have abundant groundwater resources, are not considered here because of the availability of other surface water resources in those regions and/or because numerous investigations have been conducted or are underway in these important parts of the Murray-Darling Basin. Similarly, much of the Lake Eyre Basin is also not considered (or is mentioned only briefly) because the basin is almost spatially concordant with the underlying Eromanga Basin aquifers (the Great Artesian Basin). These limitations effectively focus this literature review on South Australia, the Northern Territory and Western Australia.

In Western Australia, the Pilbara and Murchison–Gascoyne regions have modern and active coherent drainage patterns including the De Grey, Fortescue and Ashburton rivers in the Pilbara and the Gascoyne and Murchison rivers further to the south. This contrasts with most areas of arid Australia where limited or no active drainage is superimposed on the palaeovalley systems. Despite this key difference, the Pilbara and Murchison–Gascoyne regions are included in this review because of the following factors:

- The active drainage is superimposed on a palaeodrainage system which contains palaeovalley sediments and groundwater resources with many important similarities (and differences) to other regions;
- The rivers are all ephemeral with wide temporal variations in the magnitude of flows;
- Water supplies for communities, towns and mines are dominantly sourced from palaeovalley groundwater; and
- The interaction between surface water and groundwater systems provides a significant difference to most other study regions.

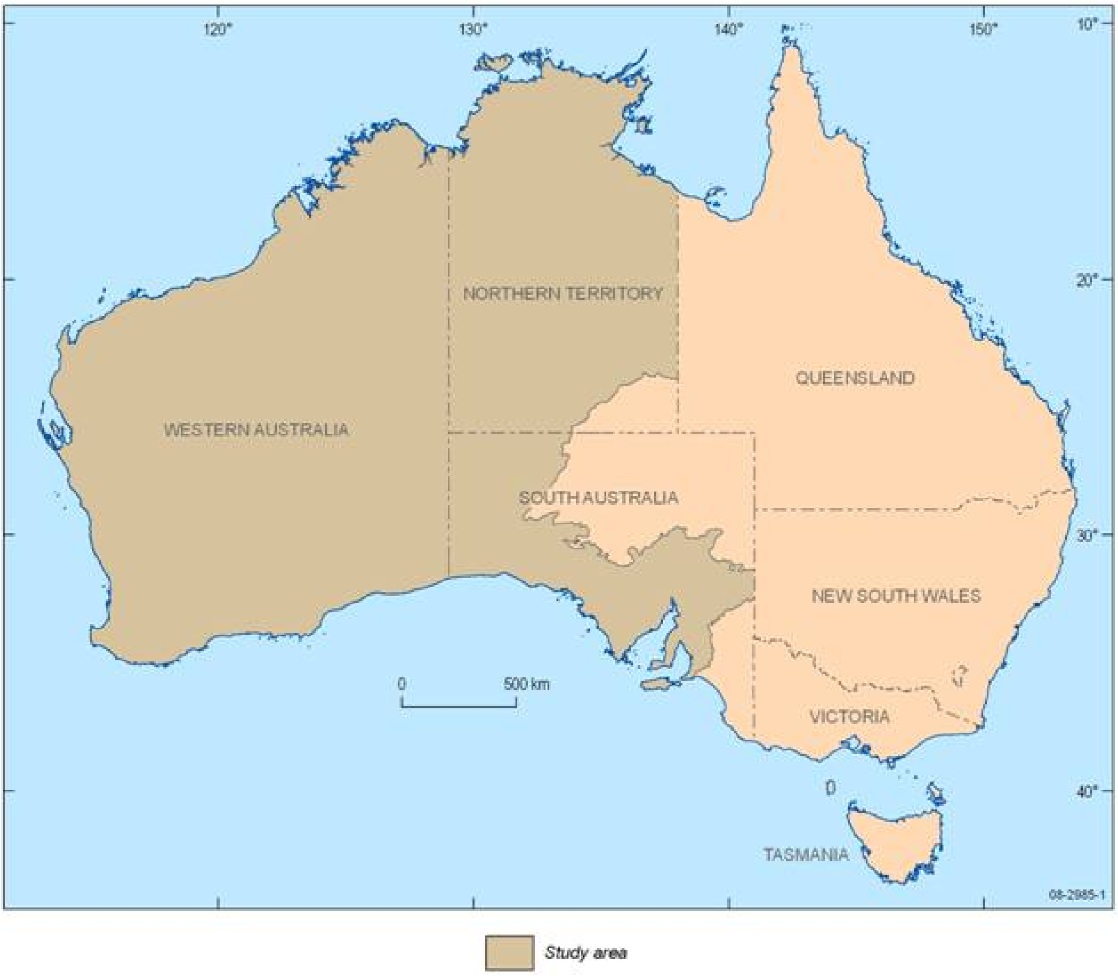


Figure 1.1: *The arid to semi-arid area of interest for the Palaeovalley Groundwater Project includes Western Australia and most of South Australia and the Northern Australia. Eastern Australia, with relatively greater access to surface water resources and other groundwater systems, such as the Great Artesian Basin, is excluded from this study.*

1.3. NOMENCLATURE

There is widespread confusion and misuse of terms in the literature regarding palaeovalleys in Australia (Clarke, In Press). As discussed by de Broekert and Sandiford (2005) and in more detail by de Broekert (2002), there is a clear geomorphic distinction between the terms 'channel' and 'valley' which should also be observed when discussing palaeoforms. Valleys are negative landforms which may contain rivers (or glaciers, wind flows etc.), whereas channels are particular landform elements within rivers (Figure 1.2). A channel lies in the thalweg of a stream, is occupied by water and is the deepest, central part containing the main river current. Thus channels and valleys are landforms that differ in scale and characteristics and are in no way interchangeable terms. Clearly, the landforms which are the focus of this review are ancient filled valleys, not solely infilled channels, and should thus be referred to as palaeovalleys. The common use of the term palaeochannels for palaeovalleys in the literature is incorrect and should be abandoned. The use of the term palaeochannel in this review will be restricted to specific discussion of ancient channel facies or forms within palaeovalley sequences. Similarly, the terms palaeodrainage and palaeoriver should not be used when referring to palaeovalleys. In this review the term palaeodrainage will only be used to refer to drainage networks of palaeovalleys.

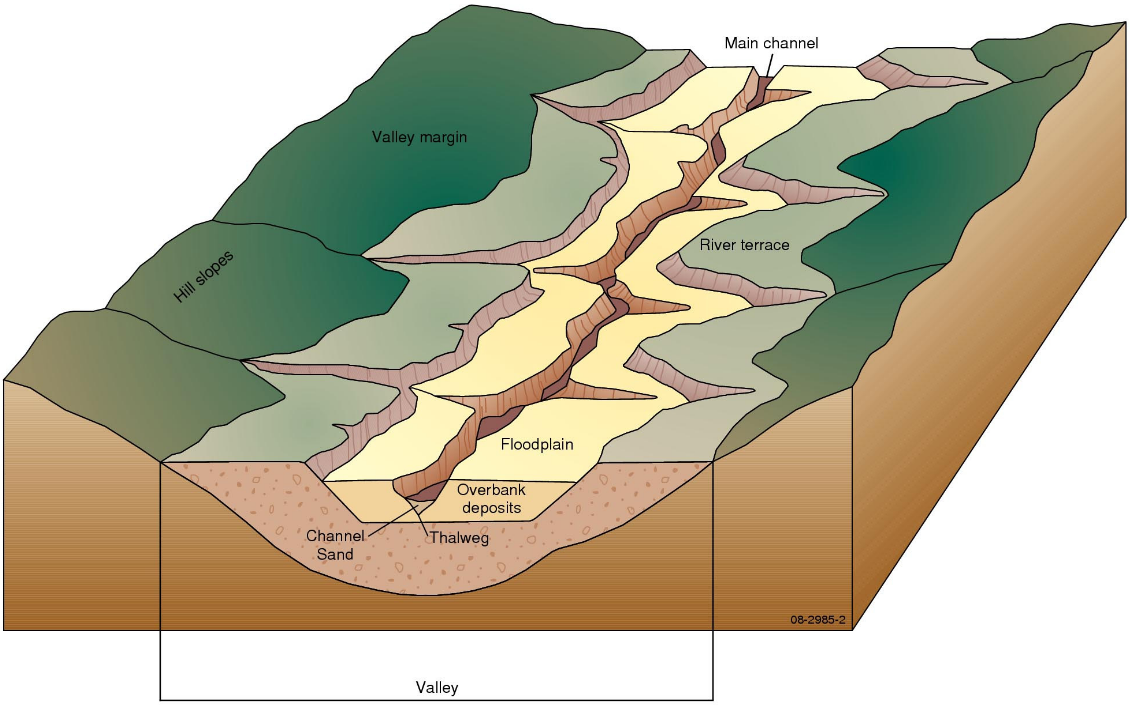


Figure 1.2: *Block diagram illustrating valley and channel landforms and terminology.*

Clarke (In Press) recently reviewed the use of palaeodrainage terminology in Australia. He suggested the following terms be adopted:

- **Palaeoriver** refers to an ancient fluvial system responsible for a particular feature.
- **Palaeodrainage** refers to a network of palaeorivers.
- **Palaeochannel** refers to the channel formed by the palaeorivers.
- **Palaeochannel deposits** refer to the sediments that infill the palaeochannels.
- **Palaeovalleys** refers to the valleys incised by the palaeorivers.

Clarke (In Press) further suggested that terms such as “deep lead”, “prior stream” and “ancestral river” should not be used, especially for international audiences.

De Broekert and Sandiford (2005) and de Broekert (2002) also discussed the distinction in the Yilgarn Province (WA) between palaeovalley systems of different age. Earlier research has commonly recognised that the extensive and intricate network of Yilgarn palaeovalleys, which were incised in the early Cenozoic and later infilled with sediments, had far more ancient roots. De Broekert and Sandiford (2005) and de Broekert (2002) explained the difference in form and origin between the larger, ancient precursor “primary” valleys and the younger, smaller “inset” valleys (Figure 1.3). They chose these terms because they encapsulated both the scale and spatial distinction between the two palaeovalley types. This distinction will probably prove to be very useful for analysis of Australian palaeovalleys, where palaeodrainages occur on landscapes that predate the Cretaceous or where thin layers of Cretaceous sedimentary rock has been removed. However, the applicability of the terms outside of the Yilgarn requires demonstration that the same distinction clearly exists and is widely recognisable elsewhere. Clarke (In Press) suggested that “inset valley” should only be used to describe a particular palaeovalley profile and not for palaeovalleys in general.

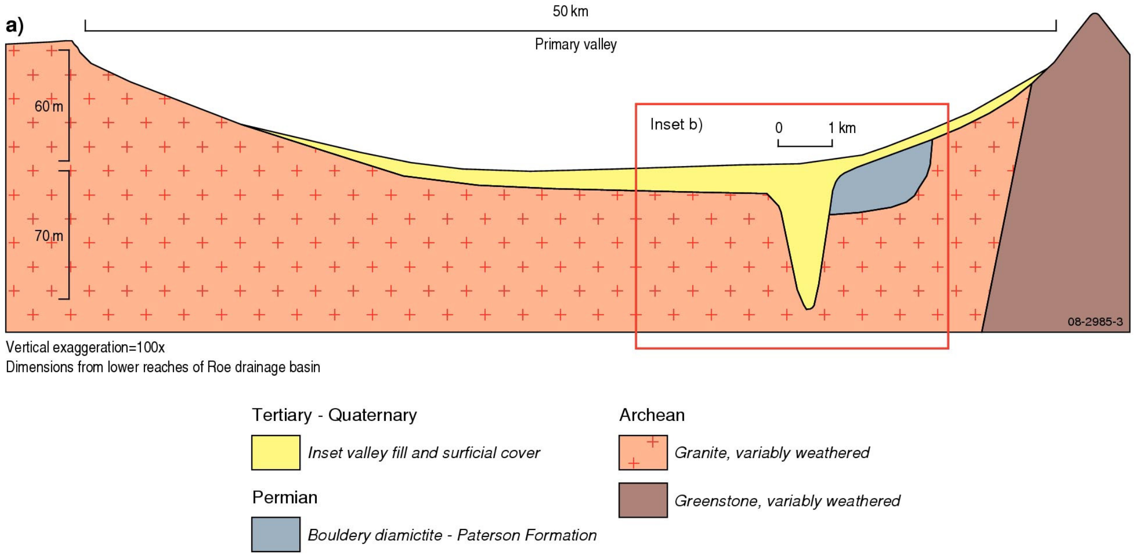
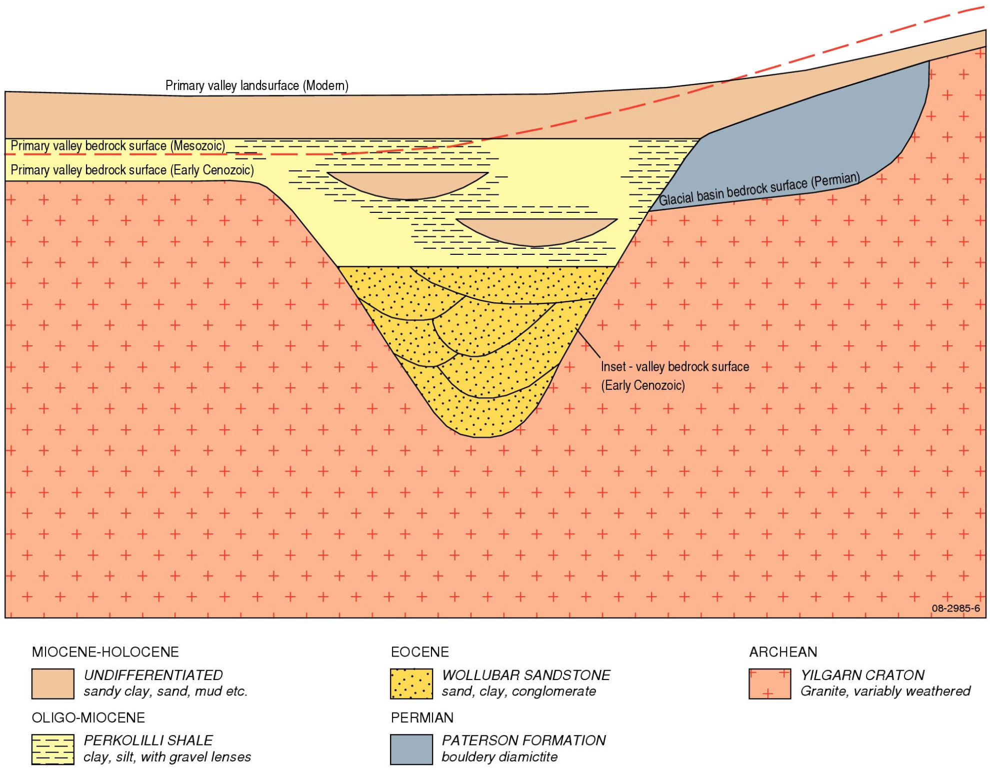


Figure 1.3: *Idealised cross-section illustrating the relationship between primary (top view) and*



inset (lower view) palaeovalleys. The inset box in (a) indicates the location of the detailed view shown below in (b), which highlights the sedimentary fill within an inset palaeovalley within the Yilgarn region of Western Australia. This figure is modified from de Broekert and Sandiford (2005) (Figure 2a).

2. Overview of Arid Zone Palaeovalleys

It is axiomatic that Australian landscapes are ancient, a feature seen to be the product of subdued tectonics, a long history of subaerial exposure and the extremely limited extent of Quaternary glaciation. This antiquity is manifest in landscape and regolith characteristics that include:

- Low relief;
- Deep weathering profiles;
- Extensive duricrust deposits;
- Thick accumulations of unconsolidated alluvium and colluvium;
- Widespread landscape salinisation; and
- Extensive networks of palaeovalleys, which have a history extending back to at least the early Cenozoic (and often much older).

In the extensive arid and semi-arid region of interest for the Palaeovalley Groundwater Project, the palaeovalley networks drain all the major pre-Palaeozoic cratonic blocks as well as the Canning and Officer sedimentary basins which contain Cretaceous and earlier-formed rocks. These drainage networks are essentially inactive today and are now largely filled with sediment. However, most are traceable as linear topographic lows, often containing elongate chains of playas, aeolian deposits and distinctive soil types or vegetation associations. In some regions the palaeovalleys are not easily recognised or continuously traceable but can be detected by various remote sensing or geophysical techniques, which discriminate discrepancies between the valley-fill and contained groundwaters and the surrounding weathered or unweathered bedrock terrane. The actual channel facies and valley thalwegs are not discernable from surface features or readily evident in remote sensing or most geophysical data. Drilling is generally required to accurately determine the internal morphostratigraphic architecture of the palaeovalleys, which may also be revealed by emerging refinements of some geophysical techniques, e.g., electromagnetic methods.

Most arid zone Australian palaeovalleys are considered to be of Cenozoic age. Much of the drainage pattern reflects continental changes resultant from the post-Mesozoic rifting and northward drift of Australia from Antarctica, and the valley-fill sediments themselves are dominantly Early to Mid Cenozoic. However, the common occurrence of palaeodrainage diversion or disruption by tectonic or river capture processes that preceded the deposition of Eocene or later valley-fill sediments demonstrates the significantly greater antiquity of at least some palaeovalleys. Indeed, it has become increasingly apparent that both pre- and post-Tertiary tectonic, landscape and climatic processes have greatly influenced the nature and patterns of palaeovalleys and their sediment infill. The fundamental palaeodrainage patterns and first-order individual palaeovalleys probably date back to the early Palaeozoic (potentially ~500 million years ago), but valley-fill deposits of this antiquity are rarely preserved. Permian glaciation, which affected much of the continent, presumably removed large quantities of transported and weathered regolith and effectively reset much of the surficial geological landscape. The palaeodrainage patterns certainly existed and developed during the Mesozoic but major rejuvenation followed the separation of Australia and Antarctica, causing valley scouring and resulting in Early to Mid Cenozoic sediment deposits (valley infill) becoming the dominant legacy. The onset of aridity in the latest Neogene has led to hydrologic stagnation, landscape salinisation and deposition of evaporite sediments, aeolian sand-sheets and dunefields. These most recent palaeovalley events have resulted in a suite of ongoing landscape processes which have moulded the surface expression of the palaeovalleys. As surface hydrologic features, the palaeovalleys are certainly relict from Miocene or earlier times, however their surficial landscape and geomorphic characteristics are still actively evolving and changing in response to Quaternary environmental processes.

Finally, it now seems apparent that the case for quiescent tectonics in post-Mesozoic Australia has been overstated. Reappraisal of adjustments to rifting, separation and northward drift of the continent (Sandiford et al., 2007; Sandiford, 2007) has demonstrated significant continental-scale tilting and other adjustments since the Palaeogene. This, in turn, has no doubt significantly influenced Cenozoic sedimentation in the palaeovalleys, by impacting on marine transgressions along with rejuvenation and changing styles of continental sedimentation. Recognition of these impacts may potentially resolve some inter-regional anomalies of later Cenozoic valley-fill histories.

2.1. HISTORY OF RECOGNITION

The existence of extensive but defunct drainage networks in inland Australia was recognised early in southern Western Australia by the explorer Carnegie (1898) who demonstrated great competence as an observer of landscape:

"These ranges, such as they are, occur at intervals of a few miles up to thirty or more, and between them scrub-covered plains, sand-plains, or flat stretches of open forest are found. In the deeper undulations, long chains of dry salt-lakes and samphire-flats are met with, occupying a narrow belt, perhaps one hundred miles in length. Doubtless were the rainfall greater, these lakes would be connected, and take the place of rivers, which would eventually find their way into the Australian Bight. Unfortunately for the comfort of travellers, this is not the case, and their water supply must depend upon one or other of the various sources already described."

In an early geological survey along the route of the prospective Trans Australian Railway, Gibson (1909) made similar observations in more detail. Jutson (1934) in his major treatise on the geomorphology of Western Australia extensively reviewed previous ideas on the origin of the chains of playas or salt lakes which characterise many of the palaeovalleys in that state. Suggested origins included:

- Wind deflation (Woodward, 1897, 1914; Maitland, 1900; Jutson, 1914, 1917);
- Glacial ice-scouring (Campbell, 1906);
- Marine erosion or incursion remnant (Montgomery, 1912, 1916; Simpson, 1923, 1926; Glaubert and Feldtmann, 1926);
- Remnants of defunct drainage (Gibson, 1909, 1912; Gregory, 1914, 1916; Honman, 1917; Talbot, 1920; Clarke, 1925); and
- Tectonic deformation (Jutson, 1914, 1917).

Jutson (1934) also mentioned frequent observations of salt-lake migration, typically towards the west and often over a planar bedrock base (Jutson, 1914, 1917, 1918; Blatchford, 1917; Honman, 1914, 1917; Talbot, 1920). Jutson's (1934) review included the statement that:

"The conclusion…that the drainage lines are the remains of old Tertiary rivers, a thesis which the writer does not consider to be proved, or even probably true."

This opinion led subsequent authors (Bunting et al., 1974) to regard him as not supporting the existence of palaeovalley networks. However, it is clear that Jutson did regard the salt lakes as occurring within palaeodrainages, but was mainly concerned with the origin of the actual modern salt lakes, which he saw as products of active deflation and salt weathering, and not as remnants of occluded river channels.

Morgan (1965, 1966) provided an early example of coherent palaeovalley mapping that aligned salt lakes in the east Murchison to north Coolgardie region. His palaeodrainage pattern showed general accord with later mapping, though he erroneously connected the Lake Moore palaeovalley in the western Yilgarn to the Avon River drainage. Certainly, the idea that the elongate lines of playas represented palaeovalley networks became the consensus view and attempts were made to map the complete palaeodrainage networks, including valley connections between salt lakes and interfluves and drainage divides by soil and vegetational characteristics. Soil scientists (Mulcahy and Bettenay, 1972; Bettenay and Mulcahy, 1972) mapped and named drainage divisions and major palaeovalleys in Western Australia and delineated the relationship between valley forms, the pattern and distribution of soils, deep weathering and ferricretes. Beard (1973) mapped palaeodrainage patterns elucidated by consistent landscape-vegetation associations, which he observed while conducting broad-scale vegetation mapping in Western Australia (Figure 2.1). In desert areas, Beard noted that mulga-parkland (commonly associated with ferricrete) dominated the interfluve higher ground, and lower palaeodrainage lines were marked by tree-savannah, desert oaks (Casuarina), sand dunes with mixed shrub steppe, and clay-pans or lakes forming drainage patterns. In the south-west, bottom-land woodlands were clearly distinct from mallee, thicket and heath of the upland interfluves. Beard (1973) followed the example and nomenclature of Mulcahy and Bettenay (1972) and named some additional palaeovalleys. These soil- and vegetation-derived palaeodrainage maps were a considerable advance in detail and accuracy and were largely concordant, but they often tended to disagree in details of drainage divide placement and drainage disruption attributable to tectonic movement or river capture. These inaccuracies resulted from the extremely low relief, compounded by the lack of accurate topographic and elevation data, particularly in upper catchments and on watersheds, and where substantial sand-sheet deposition had occurred.

The first elevation data became available from Bureau of Mineral Resources and oil company gravity surveys that produced an 11 kilometre grid of barometrically determined spot heights with an accuracy of ± 7m, which enabled contouring and improved delineation of palaeodrainage networks (Bunting et al., 1973; van der Graaff et al., 1977). In a series of papers, Beard (1998; 1999; 2000; 2002 and 2003) further refined palaeodrainage patterns in Western Australia using published 1:100,000 and 1:250,000 contoured topographic maps and 1:250,000 geological maps. In these papers, Beard examined the evolution and patterns of individual palaeovalley systems and regional drainage divisions, mapped the position of major watersheds and elucidated the long-term post-rifting geomorphic evolution of Western Australia. These later clarifications of palaeodrainage patterns extended well beyond the Yilgarn and included palaeovalleys related to the Eucla, Officer and Canning basins.

With the concept of ancient palaeodrainages extending through the Cenozoic well-established in Western Australia, similar features have been widely recognised in the Gawler Craton, Musgrave Ranges, Eucla Basin, parts of Central Australia and the Tanami Desert (where they tend to have less obvious surface expression). In these areas recognition has generally occurred by geological mapping and exploration and, in places, detailed palaeodrainage patterns have been elucidated by means of remote sensing, analysis of topographic data, geophysical surveys and drilling.

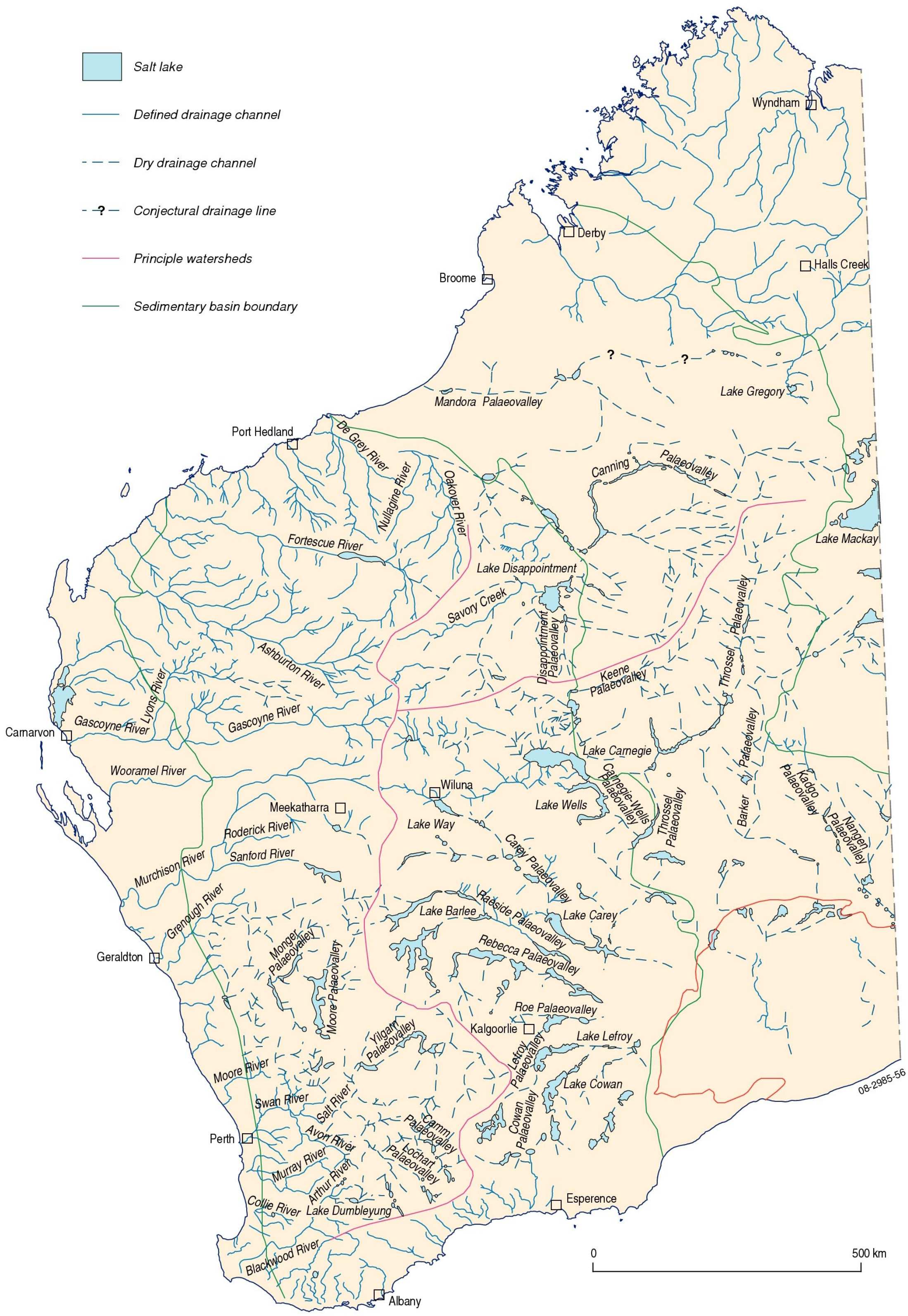


Figure 2.1: *Modified map of Beard's 1973 reconstruction of palaeodrainage systems in Western Australia.*

2.2. LOCATION IN ARID AUSTRALIA

Palaeovalleys drain all of the cratonic blocks and Precambrian uplands in arid Australia including the Curnamona Province, Gawler Craton, Musgrave Province, Arunta Block, North Australian Craton, Kimberly Basin, Pilbara Craton and Yilgarn Craton. The palaeodrainage networks are coherent, dominantly dendritic, and largely concordant with modern topographic expression. They are exorheic, indicating formation under climatic conditions considerably wetter than those prevailing today in arid Australia wherever drainage is disconnected or internal. Many of the rivers would have rivalled or exceeded the length of the longest of Australia's modern rivers in the Lake Eyre and Murray–Darling Basins. The palaeovalleys commonly rise in Precambrian basement uplands into and across Palaeozoic, Mesozoic and Cenozoic sedimentary basins, and are now largely filled with Early and Mid Tertiary sediments, and covered or obscured by Quaternary aeolian, lacustrine or alluvial sediments in the lowlands. The exception to this pattern is in the Eucla Basin where palaeovalleys are not traceable onto the uplifted Miocene Nullarbor limestone, indicating that the palaeovalleys were defunct by at least the Late Palaeogene. Only shallow drainage tracts occur on the Miocene limestone surface.

Where palaeodrainage networks have been mapped in detail using topographic information, a number of drainage diversions and disruptions due to river capture and tectonic processes have been identified (van der Graaff et al., 1977, Beard, 1973). Beard (2002) used more detailed topographic data to plot a series of palaeovalley long-profiles which demonstrated a number of anomalous horizontal or reversed gradient reaches in some palaeovalleys. It was not certain to Beard if these anomalies resulted from local or epeirogenic tectonics, Quaternary sand accumulation or disconnection between the plotted profile and valley thalweg. Drainage disruption was also clearly evident on the western and southern Yilgarn margins due to tectonic adjustments following post-Mesozoic rifting and northward drift of the continent. Drainage reversal was evident along the southern margin (Beard, 1973; Clarke, 1994) and complex disruption of the Yilgarn/Salt river system (Salama, 1994, 1997) and Moore/Monger river system (Beard, 2000) has been documented with these palaeorivers defeated and complexly diverted by uplift along the Darling Fault.

2.3. TECTONIC FRAMEWORK FOR PALAEOVALLEY EVOLUTION

Australia is well-known for its relative tectonic stability which reflects its situation as a stable continent located in an intraplate position. However, it is also the fastest moving continent on a large diverse plate and the continent is consequently relatively highly stressed (Sandiford, 2007; Sandiford et al., 2007). Marine inundation of the continental margins during the Cenozoic has been primarily controlled by the long-term eustatic regressive regime as the earth's climate cooled towards the Quaternary "ice-house" glaciations. However, variations in the extent and/or level of marine inundation around the continent reflect the influence of three distinct Cenozoic deformation modes, which resulted from northward drift of the continent and induced stress regimes (Sandiford, 2007; Sandiford et al., 2007):

- Continental-scale northeast-down, southwest-up tilting;
- Hundred metre-scale lithospheric buckling at 100 kilometre wavelengths; and
- Ten to one hundred metre-scale faulting at 10 kilometre wavelengths.

At the longest wavelengths (10^3 kilometre-scale) the continent has experienced 300-metre amplitude north-east down, south-west up tilting since the Eocene, on an axis that trends from northern Western Australia to the south-east corner of the continent, i.e., a north-west to south-east trending axis. This tilting is attributed to dynamic topographic response (variations in vertical stress transmission between convective upper mantle and the lithosphere) to the northward motion of the continent towards the equatorial western Pacific which has been a subduction zone throughout the Cenozoic and is a region of low dynamic topography and high geoid. The result is a combination of real dynamic subsidence of the northern margin and an increase in sea-level height associated with the elevated geoid. Additionally, the continent has passed across a complexly structured mantle and its movement away from a dynamic topographic low of the Australian–Antarctic discordance has resulted in dynamic topographic uplift of the south-western margin (Sandiford, 2007; Sandiford et al., 2007). At intermediate wavelengths (10^2 kilometres-scale) undulations of 10^2 metres are the least well-understood but are believed to reflect lithospheric buckling due to high levels of intraplate stress arising from plate-boundary forcing. Examples are the ~110 metre uplift of the Padthaway Ridge in southeast South Australia, ~400 metre uplift of the Flinders Ranges relative to surrounding basins in South Australia and deformation south-west of Lake MacKay, where the upper Throssel Palaeovalley is now ~80 metres lower than sections of the palaeovalley immediately downstream (Sandiford et al., 2007). At short wavelengths (10^1 kilometres) undulations of 10–100 metres are associated with cumulative fault movements which are also generally associated with intraplate stress related to plate-boundary forcing. Examples include ~120 metres displacement of Oligo–Miocene and Pliocene shoreline deposits on the northern flanks of the Otway Ranges in Victoria and ~190 metres displacement of Oligo–Miocene marine limestones by the range-bounding Willunga Fault in the Mt Lofty Ranges, South Australia (Sandiford et al., 2007).

The tectonic framework for palaeovalley evolution of the southern part of Western Australia is outlined by Clarke and Alley (1993), Clarke et al. (2003) and George et al. (2008), particularly with regard to palaeogeographic trends, regolith evolution and the emergence of salinity in the WA Wheatbelt. The complex architecture of palaeovalleys is extended back to the Jurassic. Most of the inland drainage systems are inactive today and exist as sumps – rather than channels – for surface drainage. Bedrock relief beneath ancient valleys commonly provides structural control, promoting accumulation of thick sediments off-axis and influencing geomorphic development, including inversion of relief through post-Eocene differential removal of the former interfluves of exposed bedrock. Two Eocene marine incursions along the southern margin of Australia substantially influenced palaeovalley evolution. Sediments deposited during these transgressions infill palaeovalleys to distances of 300 kilometres inland from the present coastline and occur at elevations of at least 300 m Australian Height Datum (Clarke et al., 2003; George et al, 2008). This reflects the magnitude of marine flooding or of subsequent epeirogenic uplift (Beard, 1999), continental-scale tilting (Sandiford, 2007) or a combination of these mechanisms.

In central Australia an intracratonic basin-and-range province developed during the Cenozoic (English, 2002). Ancient faults in the Proterozoic Arunta Province which were reactivated during the Devonian–Carboniferous Alice Springs Orogeny subsequently played a pivotal role in the development of Cenozoic basins, geomorphic structures and aquifer systems. Cenozoic basin inception is attributed to flexural down-warping along the east-striking, northward-dipping Redbank Thrust Zone, immediately north of the West MacDonnell Ranges (English, 2002). The down-thrown fault block was the former hanging wall, composed of mafic granulite facies rocks, which are denser than amphibolites and granites of the fault block to the adjacent south; the structural configuration of the region consequently may have been mechanically unstable from the Alice Springs Orogeny onwards. Down-warping of approximately 200 metres during the Cenozoic produced a trough that became an initial depocentre for Eocene sedimentation in Lake Lewis, Burt and Mount Wedge basins immediately north of the ranges, beneath the present-day piedmont zone. Such down-warping may also have resulted in capture of major mountainous catchments in the MacDonnell Ranges and reversal of prevalent former southward flow – that fed the Finke River and Lake Eyre system – to northward flow to Lake Lewis Basin (English, 2002), with very major impacts on sedimentary, hydrologic and hydrogeologic processes in the evolving Cenozoic basins (Sections

4.3.1 and 4.3.2, below). This Cenozoic deformation may have been coincident with the timing of rapid drift of Australia away from Antarctica in the Mid Eocene. At this time formerly prolonged north–south compressive stresses relaxed and large basins in the south of the Australian continent were subsiding; Sandiford (2007) and Sandiford et al. (2007; 2009) also proposed continent-scale tilting and lithospheric buckling. Significant sedimentation commenced in the Cenozoic basins of the central Australian uplands at this time (Section 4.3.1.1). The tectonic framework and the role of faults and buried and outcropping basement highs continue to influence the central Australian Cenozoic basins, including partitioning of aquifers, groundwater flow paths and the location of discharge zones (Section 4.3.2).

2.4. PALAEOVALLEY AGE AND ORIGIN

Many of the basement upland palaeodrainage source areas have been sub-aerially exposed since the Precambrian or Late Palaeozoic. Therefore it is highly likely that many of the palaeovalleys, or their precursors, have been in existence since Mesozoic or even Palaeozoic times; a number of such ancient features have been reported. In the Davenport Ranges of the central Northern Territory Stewart et al. (1986) demonstrated that river terraces, which were originally interpreted as Tertiary age, were overlain by fossiliferous Cambrian marine sediments. Also in the Northern Territory, Wilford (2000) has identified palaeovalleys in the Tanami–Granites region that contain Cambrian Antrim Plateau Basalts, which flowed down the valleys burying alluvial sediments and deeply weathered valley-side basement rocks. Further north, on the North Australian Craton, Nott (1994) has identified range and valley landscapes as being pre-Cretaceous in age, which were previously correlated to Cenozoic erosion cycles. A number of studies (Beard 1973, 1998; van der Graaff, 1977; Ollier, 1988a; Ollier and Pain, 1996) have concluded that the drainage patterns and stratigraphic relationships of deep weathering and valley fill demonstrate a Mesozoic antiquity for the Yilgarn palaeovalleys. De Broekert and Sandiford (2005) demonstrated that the major Yilgarn palaeodrainage pattern mapped by earlier researchers was established in the Mesozoic and consisted of sub-rectangular to rectangular shaped valleys some 20–100 kilometre-wide with very low gradients (0.04–0.008) and low relief (50–150 metres). These were termed “primary valleys”.

It is likely that the major Permian glaciation that was widespread across arid Australia truncated much of the pre-existing landscape. Most palaeodrainage patterns, palaeovalleys and contained sediments in the glaciated regions are thus likely to be post-Permian. Van der Graaff et al. (1977) suggested that parts of the Ponton Creek Palaeovalley and some palaeovalleys near Lake Disappointment followed Permian glacial valleys which may or may not have been buried and exhumed. In the central Australian ranges near Alice Springs, Mabbut (1967) also reported rivers which cut across the ranges and follow patterns established during the Late Palaeozoic. English (2002) related the geomorphic structure in central Australia to the Alice Springs Orogeny, including the prevalent north and south trending drainage lines that orthogonally cut across the bedrock strike. Pervasive north-directed joint patterns are related to the east–west minimum stress direction of the Alice Springs Orogeny; these joints occur in many different rock types, including hard quartzite units which are mostly resistant to erosion.

2.5. STRATIGRAPHIC ARCHITECTURE AND AGE OF VALLEY FILL

Although palaeodrainage systems across much of the arid zone may extend back to post-Permian glacial landscapes, the palaeovalleys evident today are predominantly infilled with Cenozoic sediments. Ollier (1988a; 1988b) described deep weathering profiles in Yilgarn bedrock which extend across interfluves and valley sides of the palaeodrainage networks and are buried by the Cenozoic valley fill material (which themselves lack similar deep weathering effects). He interpreted this as clear evidence that the deep weathering episode was Mesozoic in age and widely affected the Yilgarn landscape, above the level of the Cretaceous marine incursion. Later work by

Commander et al. (1992) recognised that deep weathering in the Yilgarn was invariably deepest adjacent to the palaeochannel sediments. They interpreted this to indicate that palaeovalley incision into fresh bedrock was followed by post-infilling weathering (post Late Eocene), which was promoted by groundwater circulation in the palaeochannel sediments.

During the Cretaceous, marine incursion and associated sedimentation at lower topographic levels extended into palaeovalleys which had formed following the Permian glaciation event (Wilford, 2000). However, it was undoubtedly the post-Mesozoic tectonic adjustments (after rifting and northward drift of the continent) that resulted in sufficient rejuvenation to remove pre-Cenozoic valley fill and establish the palaeodrainage networks evident today. These palaeovalleys extend from bedrock uplands across Palaeozoic and Mesozoic basins and platform cover sediments. The main period of erosion probably occurred from the Palaeocene to Early Eocene, and may have been associated with transition from seasonal to wetter year-round rainfall patterns (Langford et al., 1995). In a recent review of Yilgarn palaeovalley evolution and nomenclature de Broekert and Sandiford (2005) demonstrated that large Mesozoic "primary valleys" were incised by smaller "inset valleys" (Figure 1.3). This incision event, which is indirectly dated to the early Middle Eocene, combined with the absence of Mesozoic valley sediments indicates that widespread stripping of sediment and erosion of a small thickness of bedrock beyond the inset-valley flanks produced a regional unconformity. Incision of the inset valleys was not caused by eustatic base-level lowering but was initiated by epeirogenic uplift at the beginning of the early Middle Eocene. Additionally, climatic cooling and the consequent reduction in evapotranspiration and increased river discharge rates may have contributed to valley formation in the Early to Middle Eocene (de Broekert and Sandiford, 2005).

In common with most intra-continental Cenozoic sedimentary basins, palaeovalley infill sediments typically consist of a two-fold stratigraphic sequence; Eocene channel or estuarine deposits are overlain by generally finer-grained sediments of Late Oligocene to Miocene age (Figure 2.2). Suggestions of additional palaeovalley sedimentation in the Pliocene at a number of sites in the arid zone are poorly constrained chronologically. Interpreted Pliocene sediments are also of limited significance over most of the project study area, except near the western Yilgarn margin where Cenozoic tectonic uplift and drainage disruption resulted in the accumulation of some significant Pliocene deposits. The Mid to Late Eocene sediments are dominantly coarse-grained fluvial sands and basal gravels, deposited under wet climatic conditions. They are chronologically constrained by well-preserved palynomorphs sourced from organic-rich and lignitic palaeovalley infill sediments. Palynological studies indicate that rainforest conditions prevailed, varying from mesothermal (moderate temperatures) to megathermal (hot temperatures) both across the continent and through time. At lower elevations and on marine margins multiple eustatic sea-level rises led to marine and estuarine incursions into the lower portions of palaeovalleys. Marine incursions characterise the Eucla Basin margin palaeovalleys, particularly those along the eastern margins flanking the Gawler Craton and less noticeably along the south-eastern margins of the Yilgarn Craton where epeirogenic uplift was more effective.

The second phase of Cenozoic palaeovalley sedimentation probably extended from the Late Oligocene to Mid Miocene and was characterised by relatively lower energy, generally exorheic drainage systems. Fine-grained, lacustrine and dolomitic sediments dominate in the Lake Eyre Basin and in the palaeovalleys of the eastern Eucla Basin margin, whereas fine-grained sediments and valley calcrete deposits are abundant in the western Eucla Basin, Yilgarn Craton and northern Australian palaeovalleys. In central Australia it is likely that most palaeovalley aquifer horizons are post-Eocene in age.

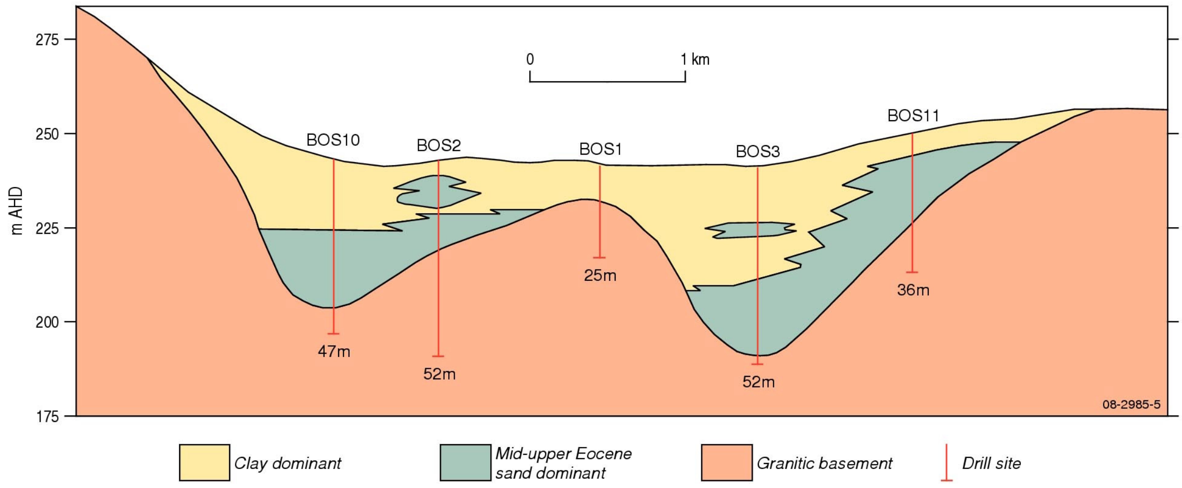


Figure 2.2: *Idealised cross-section of the Beaufort Palaeovalley in the Blackwood River catchment, South-West Drainage Division of Western Australia. Figure is modified from Waterhouse et al. (1994) (Figure 3).*

Post-depositional ferricrete and silcrete can occur in both the older and younger Cenozoic sedimentary phases described above, however calcrete is only known in the younger phase. The Early Oligocene to Late Miocene and perhaps the Pliocene are likely times of silcrete formation (Langford et al., 1995; Drexel and Preiss, 1995). Coarser-grained Eocene fluvial sediments function as important palaeovalley aquifers in many parts of arid Australia, and are commonly overlain and confined by the later-formed deposits of fine-grained sediments.

During the Quaternary, aeolian sand sheets and dunefields covered portions of the palaeovalleys at a time when connected exorheic drainage and significant fluvial or lacustrine deposition had ceased. Playas with evaporites developed in many palaeovalleys in response to the evolution of saline groundwaters; these are active landscape elements, which can migrate, and are also sites of significant groundwater discharge characterised by little net sediment accumulation. Ephemeral channels connect some playas, but although these can flow in extreme rainfall events in the modern environment they are also characterised by minimal sediment accumulation.

2.6. SEDIMENTARY FACIES

The basal Eocene palaeovalley sediments are fluvial fine- to coarse-grained sands and gravels, generally in the range of 20–40 metres thick. These sandy deposits commonly fine-upwards from basal gravels and may contain carbonaceous material that can grade vertically and laterally into fine-grained lignitic facies. Lignite horizons can be 10–20 metres thick and grade laterally to fine-grained clastic material. These sediments represent deposition in an aggrading fluvial valley plain with braided river deposits indicated in some areas, such as the Lake Eyre Basin (Callen et al., 1986). Lignites and carbonaceous deposits formed in swamps and valley lakes associated with the fluvial systems. In the lower Eucla Basin margin, palaeovalleys were inundated by Eocene eustatic transgressions; here lignite facies can grade laterally to marine carbonates and spicular carbonaceous clastics and grade vertically to marine sediments (Alley et al., 1999). Basal marine sediments are dominantly poorly fossiliferous clastics or shallow marine limestones, with fragments of bryozoans, coralline algae, molluscs, echinoids, and foraminifera, which contain minor clastic material (Alley et al., 1999). These are commonly overlain by spongolites which variably contain 25–90% siliceous spicules (Drexel and Preiss, 1995).

The finer-grained Late Oligocene to Miocene palaeovalley sediments unconformably overlie the Eocene sequence and adjacent deeply weathered bedrock of the valley sides. These sediments include some coarse- and fine-grained fluvial channel clastics but are dominantly very fine-grained vertical accretion valley deposits or lacustrine deposits indicative of less effective discharge than the Eocene river systems. Dolomite and dolomitic clay lacustrine deposits are widespread in the Lake Eyre Basin (including the palaeovalleys), and in the palaeovalley systems of central Australia and the eastern Eucla Basin margins. These alkaline lake deposits are clastic-poor and dominated by chemical sediments, indicating ineffective discharge – a probable consequence of a more arid climate and reduced gradient due to increased valley-fill thickness. Valley calcrete deposits, probably of similar age and origin, are widespread in the northern Yilgarn Craton (Mann and Horwitz, 1979; Arakel and McConchie, 1982) and in the Pilbara, especially the Oakover Formation (Williams and Trendall, 1998) and the Millstream Dolomite in the lower Fortescue valley (Barnett and Commander, 1985) (Figure 2.3 and Figure 2.4).

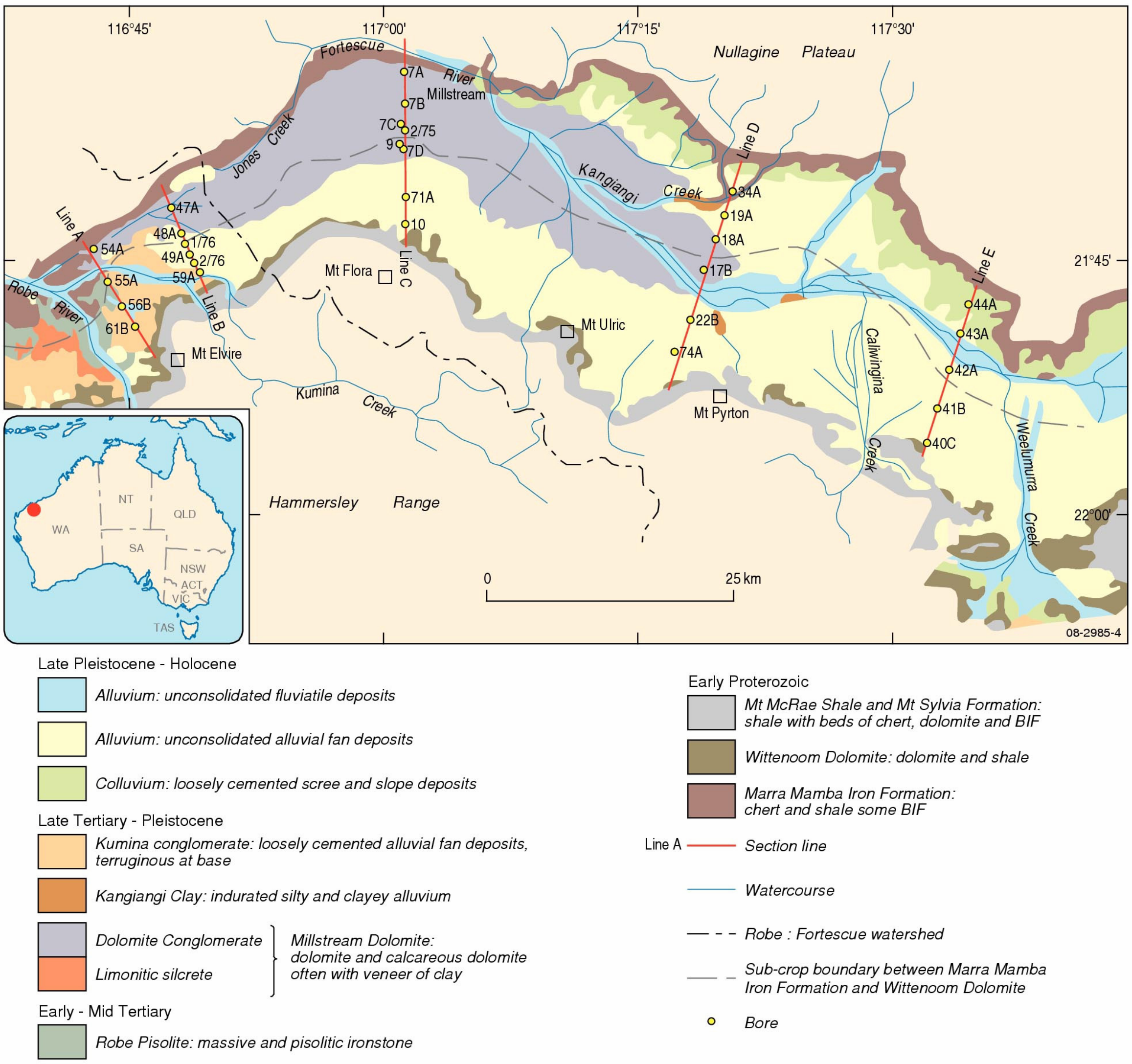


Figure 2.3: *Geological map of the Lower Fortescue Valley showing the widespread distribution of the Millstream Dolomite, a major valley-fill deposit in the Pilbara. Figure is modified from Barnett and Commander (1985) (Figure 3).*

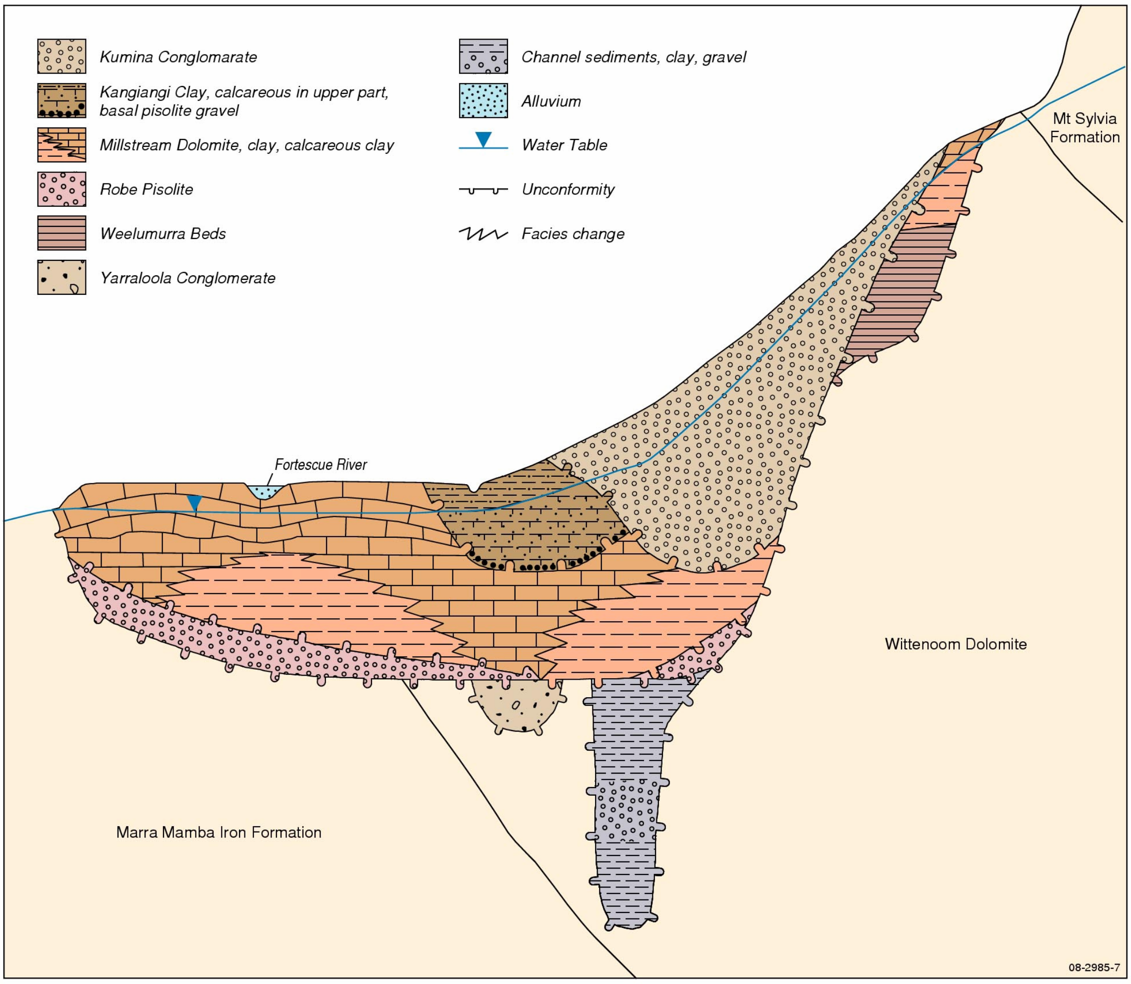


Figure 2.4: *Idealised cross-section of the Lower Fortescue Valley demonstrating the stratigraphic relationship between palaeovalley sediment units. The Millstream Dolomite represents a major component of the sequence. Figure is modified from Barnett and Commander (1985) (Figure 5).*

The stratigraphic relationships of Oligo-Miocene sequences in the western Eucla Basin and the Yilgarn Craton seem problematic. Near Kalgoorlie, Commander et al. (1992) described a mottled, dominantly lacustrine, clay-rich unit (Perkolilli Shale) overlying basal fluvial lignitic sands, with the latter palynologically well-constrained to the Middle Eocene. Anand and Paine (2002) have confirmed this stratigraphic sequence to be widespread in the Yilgarn. The apparently conformable contact between the fluvial sands and the overlying lacustrine clays led Commander et al. (1992) to assume an Upper Eocene age for the Perkolilli Shale; similar ages were assumed for equivalent facies in other Yilgarn palaeochannels by Anand and Paine (2002). Pollen is not preserved in these sediments and the age is therefore uncertain. Clarke (1993) suggested an Oligo-Miocene age for similar, but undated, clay-rich lacustrine sediments containing dolomite at a similar stratigraphic position in the Lefroy and Cowan Palaeovalleys, and also suggested that these were lateral equivalents of the Perkolilli Shale, thereby implying an Oligo-Miocene age for the latter. In a later review of the Eocene stratigraphy of the Eucla Basin, including the palaeovalleys, Clarke et al. (2003) recommended abandoning use of the term Perkolilli Shale but appeared to accept its age as Upper Eocene. Anand and Paine (2002) showed fine-grained lacustrine facies in both the Upper Eocene and Oligo-Miocene of many palaeovalley sections evident in open-cut mines in the Yilgarn.

However, their descriptions provided scant details about the putative Oligo-Miocene sediments, probably reflecting the chronological and stratigraphic uncertainties. Given the widespread conformity of Cenozoic basin and palaeovalley deposits in Australia to the two-fold Eocene and Oligo-Miocene stratigraphic sequence (as described above), it seems likely that deposits in the Yilgarn should be similar, unless uplift of the Yilgarn due to continental-scale Cenozoic tilting has seriously impacted deposition timing and style.

Post Oligo-Miocene sediments occur in many palaeovalleys, but these tend to be mostly minor and vary regionally. Fine-grained Pliocene sediments, similar to the Oligo-Miocene unit, are reported from a number of west Yilgarn palaeovalleys, especially where drainage has been disrupted by Cenozoic tectonic activity. Additionally, colluvial and alluvial sediments occur in many arid zone palaeovalleys, including those in the north-eastern Yilgarn where Johnson et al. (1999) reported deposits up to 60 metres thick with significant amounts of good-quality groundwater.

2.7. SECONDARY DEPOSITS AND DURICRUSTS

Discussion of deep weathering and associated deposition of chemical sediments formed by secondary weathering, herein generally termed duricrusts, is a major research topic by itself and is only briefly outlined in this review. The secondary duricrust deposits, which are typical of palaeovalleys and the landscape in which they are incised, chiefly consist of **ferricrete**, **silcrete** and **calcrete**. Although there is a good understanding of the nature and expression of these duricrust deposits, widespread uncertainty and disagreement exists about their depositional processes, ages and genetic connotations, particularly for ferricrete and silcrete. It is likely that the onset of ferricrete formation is pre-Cenozoic and precedes silcrete formation, which probably dominantly occurred in two distinct Cenozoic episodes. In most areas calcrete formation likely represents the final phase of secondary duricrust deposition, and is thought to be related to the onset of arid conditions in the Neogene. However, iron and silica mobilisation has continued, at variable rates, throughout much of the Cenozoic. The stratigraphic relationship between ferricrete, silcrete and calcrete is a complex combination of precipitation, overprinting and replacement processes and events.

Bedrock terranes throughout the region of interest are chemically deeply weathered, in some places to depths of 100–150 metres (Anand and Paine, 2002) depending on factors such as parent rock type, landscape position, climate and duration of exposure. Deep weathering processes involve the physical and chemical breakdown of primary minerals, leaching of soluble components and the formation of a combination of secondary and resistant minerals, which results in an enrichment of iron, aluminium and silica at upper (near-surface) bedrock levels. Widespread deep weathering of Precambrian and Lower Palaeozoic rocks has resulted in the common occurrence of secondary iron precipitation at the surface. Until recently, these ferricrete deposits have generally been called ‘laterite’ and, in accordance with the classical understanding of that term, were interpreted as having formed on an extensive, stable and low-relief landscape under a seasonally humid tropical or sub-tropical climate. More recently, it has been recognised that the mobilisation and deposition of iron during weathering can occur by a variety of mechanisms in different landscapes and climatic regimes (Anand and Paine, 2002); these mechanisms require sufficient rainfall to promote chemical weathering and leaching of minerals, tectonic stability to preserve the secondary products, and sufficient time for reactions to occur. Certainly there is widespread evidence that deep weathering and significant formation of ferricrete preceded Palaeocene to Early Eocene incision of the palaeovalleys, and reworked ferricrete materials occur in the basal palaeovalley infill sediments (Anand and Paine, 2002). In contrast, however, P. Commander (pers. comm. 2008) suggested that the basal gravels are quartz-dominated and that reworked ferricrete is rare.

Palaeovalley infilling sediments, in turn, have also been weathered, and this is described as deep weathering in some studies. The palaeovalley sediments are commonly modified, cemented or replaced by secondary duricrust deposits. Ferruginisation of palaeovalley sediments across the Yilgarn Craton is widespread as megamottles (Anand and Paine, 2002) or nodules, pisoliths or massively cemented zones at upper levels; mostly, but not exclusively, above the modern level of the watertable (Anand and Paine, 2002; Commander et al., 1992). Secondary silicification of palaeovalley sediments or silcrete formation is also widely reported. In the Yilgarn, silicification at the base of the lacustrine upper unit (at the contact with the underlying palaeochannel sands) was reported at one location by Commander et al. (1992). In the Lake Eyre Basin and other adjacent parts of South Australia silcrete deposition in a variety of forms occurs in palaeovalley deposits and other landscape elements and is generally ascribed to two periods of silicification – Oligocene to Early Miocene and Pliocene (Drexel and Preiss, 1995). However, direct dating of silcrete has not been successful and the assumed ages of formation depend on speculative stratigraphic ages determined from relative relationships evidenced from overprinting, reworking and known gaps between sedimentary depositional episodes. English (2001) described a strong case for ongoing Quaternary silica precipitation at the sub-basin scale in central Australia in response to an interconnected series of hydrochemical reactions in shallow groundwater.

Calcrete deposits occur widely in palaeovalleys across the arid zone, particularly in the upper near-surface sediments. They are deposited from laterally migrating shallow groundwater, and form as replacements of a variety of sedimentary and regolith materials. They have variable magnesium contents, ranging from calcite to dolomite. Calcrete deposits are typically up to 10 metres thick, although thicker deposits may exist, e.g., the 30 metre thickness of Millstream Dolomite reported in the lower Fortescue valley (Barnett and Commander, 1985). Calcrete deposits may extend across the entire width of the host-palaeovalley, typically beyond the limits of the underlying, narrower palaeochannel sand facies. Continued precipitation of calcrete can lead to expansion of the calcrete body above the original palaeovalley surface, resulting in positive metre-scale relief (Wilford, 2000).

Deposition of secondary duricrust deposits can have significant implications for groundwater storage, mobility and composition. Certainly where duricrusts are massive and form interstitial cement in primary materials they may reduce the storage capacity and transmissivity of aquifers and increase the confining capacity of fine-grained sediments in the overlying upper palaeovalley sediments. Solution processes result in enhanced porosity and permeability of palaeovalley calcrete; such deposits can, accordingly, function as significant palaeovalley aquifers, often with much better water quality than occurs in the underlying alluvial facies of the palaeovalley aquifers. The latter seems particularly the case where cavities and vughs in karstic calcrete have been silicified (English, 2002).

2.8. MODERN EXPRESSION AND LANDSCAPE ROLE

Implicit in the usage of the prefix ‘palaeo’ with respect to palaeovalley, palaeochannel and palaeodrainage is the concept that these are relict or defunct fluvial entities or systems. It is certainly true that they are effectively defunct as modern rivers. In some palaeovalleys there are minor surface channels which can connect playas and carry flood-flow in extreme modern rainfall events, such as overflow from Lake Raeside to Ponton Creek and eventually to the Nullarbor caused by extremely high rainfall associated with Cyclone Bobby in April 1995 (Johnson et al., 1999). However, the long-term flux of sediment or surface water in these systems is virtually zero and they can be regarded as vestigial river valleys. Notwithstanding, the palaeovalleys are clearly still active depositional sites for non-fluvial Quaternary sedimentation, which dominantly consists of aeolian sand deposits but some alluvial fans may also be active. Importantly for this study, the palaeovalleys are active groundwater systems; the groundwater and surficial environment interact in an actively evolving landscape which produces a gradational sequence of landforms.

Palaeovalleys in the arid zone are mostly covered by Quaternary aeolian sand deposits, in the form of sand sheets or dunefields. In most regions the sand cover is not sufficiently thick to infill the topographic expression of the palaeodrainage pattern or to mask the trace of individual palaeovalleys. In fact, selective development of dunes in palaeovalley tracts can enhance their visibility as distinct landform features. Generally the combination of topographic expression, sediment signature, weathering, soils, groundwater and resulting vegetation assemblages render palaeovalleys evident on the ground or via air-photo or satellite imaging. Sand deposits only completely mask the palaeovalleys in the major dunefields of the arid zone, such as the Simpson, Great Sandy or Great Victoria Deserts. However, even in these dunefields the topographic expression of the palaeodrainage pattern is mostly still evident in high-resolution digital elevation model (DEM) data.

2.8.1. Playas (Salt Lakes)

The most characteristic visible feature of the inland palaeodrainage networks are playas or salt lakes, which occur in all palaeovalleys but vary greatly in size, shape and pattern (Table 2.1 and Figure 2.5). An implicit assumption in many earlier palaeovalley studies is that the playas somehow either reflect the dismembered palaeovalley channel or are a relict of valley-lakes after reduced levels of flow (due to aridity) resulted in the channel or lake being occluded by aeolian sands. This assumption erroneously regarded the playas as relict or defunct landscape elements of the palaeovalley fill. The playas are a dynamic and active part of the modern landscape and a product of a new hydrologic regime involving saline palaeovalley groundwater interaction with the landscape surface. Playas are also an important component of the groundwater flow system, being a major site of groundwater discharge from palaeovalley aquifers. This aspect of the playas was evident to some early researchers who recognised that the playas were dynamic landscape elements and that they migrated upwind due to a combination of salt weathering and deflation (Jutson, 1914, 1917, 1918; Blatchford, 1917; Honman, 1914, 1917; Talbot, 1920).

Table 2.1: Summary of main playa types associated with arid zone palaeovalleys.

TYPE	DESCRIPTION	EXAMPLES
1	Chains of small disconnected basins with variable, often large, spacing	South-west Yilgarn palaeovalleys (WA); eastern Eucla Basin palaeovalleys (SA); Officer Basin to western Eucla Basin palaeovalleys (SA, WA)
2	Elongated chains of closely spaced playas, some with connecting channels	Serpentine Lakes Palaeovalley (WA), Percival Lakes/Lake Auld section of the Canning Palaeovalley (WA)
3	Groups of very large and irregularly shaped playas	Moore-Monger Palaeovalley (WA) and Lake Deborah section of Yilgarn-Salt River Palaeovalley of the eastern Yilgarn (WA); all eastern Yilgarn and western Eucla Basin margin palaeovalleys (WA)
4	Very large irregular single playas	Lake Disappointment (WA) and Lake MacKay (NT-WA)

The relationship between playa size and morphology and evaporite formation can be used to explain different patterns of palaeovalley playas (Table 2.1). These characteristics and associations can also provide a useful first-pass predictive tool for understanding salinity and groundwater flow characteristics from the pattern of playas in a given palaeovalley. For example, where palaeovalley groundwater flow is relatively effective and extends long distances down-valley, salinity will be relatively low and playas will be few and small. However, there are many mechanisms which can occlude the hydraulic conductivity of palaeovalley aquifers such as:

- Aquifer facies changes;
- Deposition of secondary cementing deposits, such as ferricrete, silcrete, and calcrete; and
- Tectonic displacement.

Given the Middle Eocene age for the dominant fluvial sand aquifers in arid zone palaeovalleys, there has been ample opportunity for these major processes to occur (either singularly or in combination).

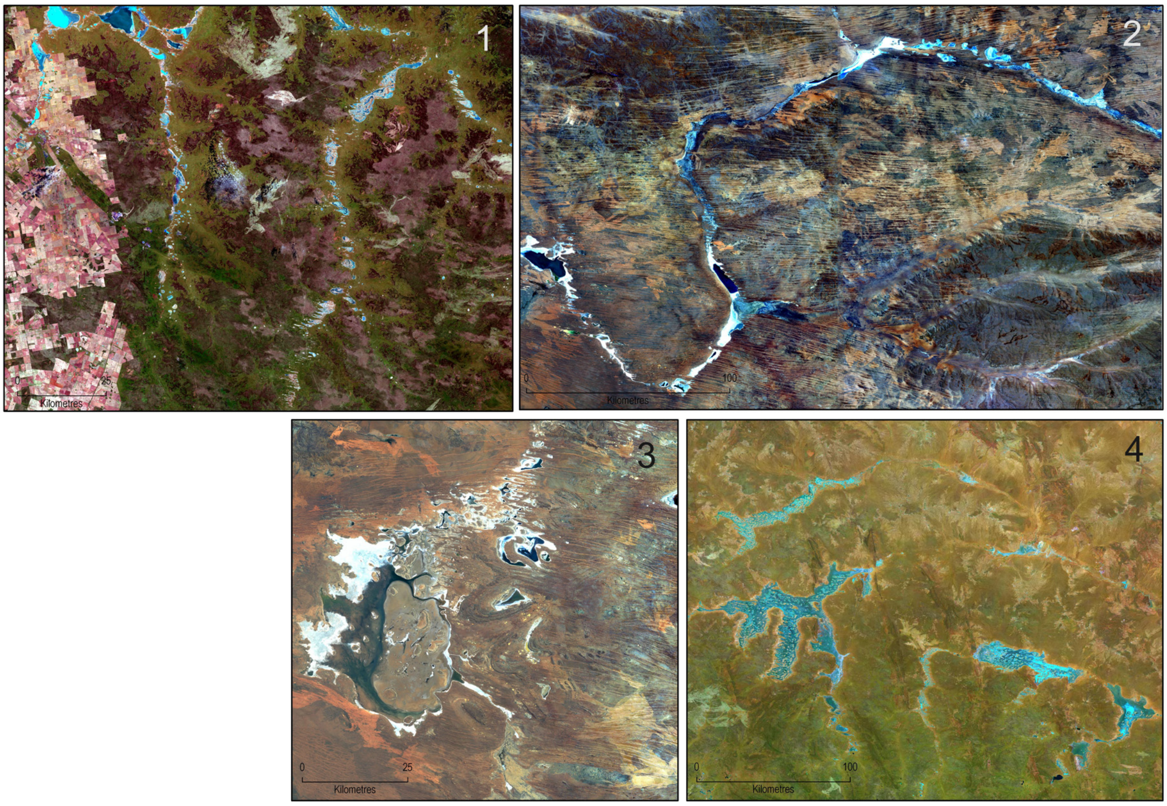


Figure 2.5: *Landsat images showing Australian examples of the four different playa types associated with arid zone palaeovalley systems. The image numbers shown here correspond with those in Table 2.1.*

Palaeovalleys with chains of small disconnected basins with variable, often large, spacing (Type 1, Table 2.1) are likely to be characterised by relatively efficient groundwater throughflow with comparatively little evaporative concentration at playa discharge points. Groundwater salinity over long sections of these palaeovalleys is likely to be relatively low. Palaeovalleys characterised by relatively large and numerous playas (Type 2 and 3, Table 2.1) clearly demonstrate at least some degree of occlusion of groundwater flow and the consequent evolution of higher salinities, though it is not clear if the elongate versus broad irregular-shaped playas represent a difference in occlusion mechanism or differences in original valley morphology. In the case of the Moore-Monger and

Salt/Yilgarn River Palaeovalleys of the western Yilgarn, occlusion is clearly due to tectonic damming and defeat of the palaeovalleys by uplift of the Darling Range. In the Yilgarn River palaeovalley, Lake Deborah East occurs just upstream of a resistant granodiorite body which lies across the palaeovalley and probably severely restricted the original palaeovalley incision and the cross-sectional area of the palaeovalley aquifer. Accordingly, the lake is one of the few in the Yilgarn which contains substantial stratified halite deposits (Salama et al., 1992). Very large irregular playas occupying palaeovalleys (Type 4, Table 2.1) imply a significant brine pool salt reservoir due to prolonged evaporative concentration. These are indicative of major long-term occlusion of groundwater throughflow, which implies the long-term influence of a significant tectonic disruption. Lake MacKay and Lake Disappointment are extremely large and irregular palaeovalley playas and Beard (2002) has suggested tectonic disruption in the vicinity of Lake Disappointment (but not provided details). Lake MacKay is probably also a closed and internally draining system due to tectonic disruption, but it remains poorly studied or understood.

Bowler (1981; 1986) has examined in detail the characteristics of Australian salt lakes and playas and the range of geomorphic features and sedimentary deposits they contain in a gradational sequence of environments from surface-water- to groundwater-dominated (Figure 2.6). The playas and salt lakes of palaeovalleys are at the groundwater-dominant end of Bowler's continuum and are characterised by irregular shorelines, common residual islands and low, irregular lunettes on the downwind margin. These playas rarely hold surface water and lack well-defined, smooth constructional shoreline deposits or landforms produced by a combination of wave and wind energy. Instead the playas are dominated by active geomorphic processes due to groundwater discharge and outcrop. Groundwater bevelling, whereby the horizontal watertable acts as a base level to deflation and salt weathering, commonly forms almost perfectly flat basin-floors in many groundwater playas. This process was first recognised from palaeovalley playas in the Yilgarn Craton by Jutson (1917; 1918; 1934). Aeolian deflation from the exposed playa floor can also occur in basins subject to seasonal, or drought-cycle oscillations of groundwater level, where the evolution of groundwater reaches saturation of the controlling salts, mostly halite and some sulfates. Lake-floor clayey sediments are disrupted by efflorescence of salts and deflated by saltation as sand-sized aggregates to the down-wind margin, with construction of characteristic transverse dunes (lunettes). Sub sand-sized sediment and salts are also removed from the basin by the same process and transported downwind as dust.

Groundwater playas generally have minimal sediment input and only minor oscillations of groundwater level, resulting in deflation being irregular and of relatively small magnitude. Thus, lunettes tend to be irregular and small but the combination of downwind lunette deposition and upwind groundwater bevelling can cause enlargement or upwind migration of playas. Jutson (1934) rejected the concept that palaeovalley salt lakes were relict river channel elements because they frequently had migrated laterally away from valley fill sediments and onto bedrock terranes. Salt weathering in the zone above the watertable, on the upwind playa margin, can effectively disintegrate even crystalline rocks, which results in the common occurrence of an erosional cliff-like margin on the upwind side of the basin, with a flat, bevelled rock platform below. It is likely that in these instances playas have migrated beyond the margin of inset-valley fill and onto the truncated bedrock of the wider and older primary valley (de Broekert and Sandiford, 2005). With continued evaporation, evolution of the subsurface water produces a brine pool which expands vertically and laterally, forming a deep-rooted structure merging with and affecting the local groundwater flow systems and chemical composition.

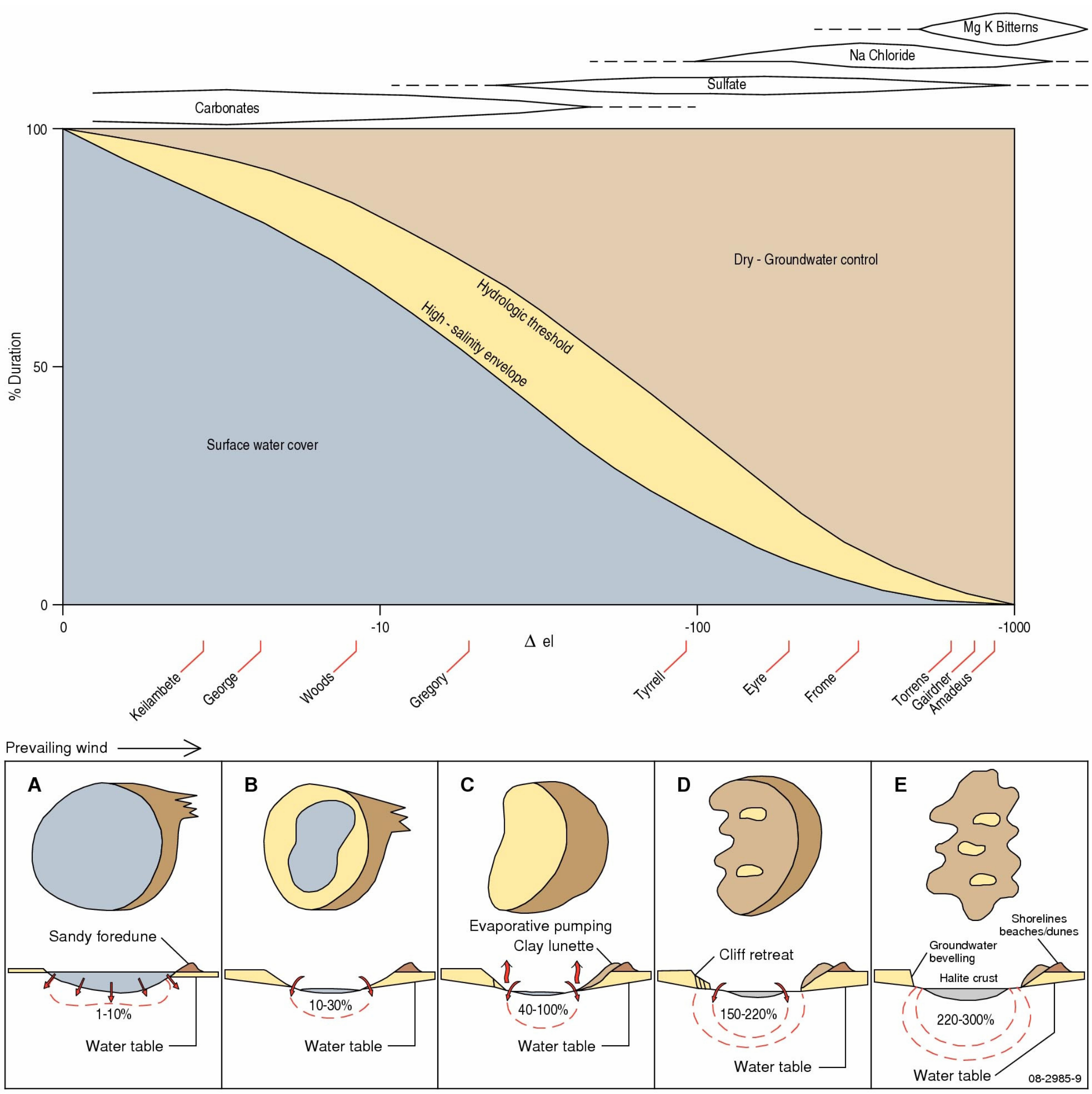


Figure 2.6: *Classification of Australian lake/playa basins across a climatic gradient which extends from humid to arid conditions. This classification scheme is based on a disequilibrium index (Δ el) which is a measure of how far the modern climatic setting of the basin examples (i.e., Lakes Keilambete to Amadeus) has deviated from that required to maintain steady-state surface-water cover. The disequilibrium index is calculated from the ratio of evaporation to precipitation (E/P), and the catchment to lake area ratio modified by an efficiency coefficient. Five lake/playa basin types, A to E, are differentiated here by morphologic and sedimentologic features, which reflect successive stages in a hydrologic series from surface-water to groundwater dominated systems, including the evolution of a sub-playa brine pool. Figure is modified from Bowler (1986) Figures 2 and 5.*

Bowler (1986) stated that the evolution of playa groundwater towards higher salinity is controlled by the length of exposure of the playa floor (lack of surface water) allowing evaporation from the capillary fringe of the watertable and the evaporative strength of the prevailing climate. This process is also influenced by additional factors such as the:

- Depth to the saturation zone, i.e. thickness of capillary fringe;
- Hydraulic conductivity and pressure gradients;
- Nature of the connection to the underlying aquifer; and
- Groundwater salinity.

A number of studies have examined the evolution of sub-playa groundwater salinity including the Amadeus–Curtin Springs area of central Australia (Jacobson et al., 1988, 1989; Jacobson and Jankowski, 1989; Jankowski and Jacobson, 1989) and at Lake Frome, South Australia, where Bowler (1986) has demonstrated the evaporative concentration of shallow interstitial water immediately underlying the basin floor. At Lake Frome, highly saline shallow groundwater, with total dissolved solids (TDS) in excess of 200,000 mg/L occurs in the centre of the basin, along with a halite salt crust (Figure 2.7). This grades laterally and vertically to lower salinity groundwater (25,000 mg/L TDS) near the basin margin, with the lowest salinity (<10,000 mg/L TDS) located over 5 kilometres away to the west. The brine pool that extends 60 metres below the playa floor acts as a large refracting lens, concentrating groundwater flow towards the margins of the halite crust and maintaining pressure discharge which concentrates flow towards the playa margins.

At Lake Tyrrell in Victoria, Macumber (1991; 1992) has investigated how the formation of an evaporation-derived groundwater reflux brine pool can induce a groundwater divide in a valley aquifer, thereby preventing seepage from the playa and down-valley groundwater flow. This process can occur even where surface and groundwater potentiometric gradients are low and no surface water topographic divide exists. This process is analogous to the situation when a bore is pumped on a sloping watertable, thereby inducing a stagnation point and groundwater divide (Figure 2.8). The playa acts as an evaporative pump and the low regional hydraulic gradients and hydraulic conductivities result in an induced groundwater divide, which at Lake Tyrell is about 6 kilometres from the playa (Macumber, 1991). The presence of high-density reflux brines beneath the lake, which contrast sharply to the wider or regional aquifer salinity, can result in a Ghyben-Herzberg interface, which forces lower-density regional groundwater towards the surface thereby ensuring capture by the playa system. The high-density reflux brines infill the aquifer and prevent down-gradient underflow of regional groundwater beneath the playa (Macumber, 1991). Once established, this system is self-perpetuating because the low groundwater gradients do not allow sufficiently high hydraulic head upwind of the playa which are required to flush the aquifer by down-gradient flow.

The system can only be overcome by two contrasting hydrologic regimes:

- Firstly, it might be achieved by increased aridity when the regional watertable and groundwater divide are lowered, but outflow is minimal due to reduced water flow budgets; or
- Secondly, outflow can occur under wetter climates when increased surface water inflow causes surface water accumulation in the lake and a consequent increase in hydrostatic head in the vertical brine column in the lake.

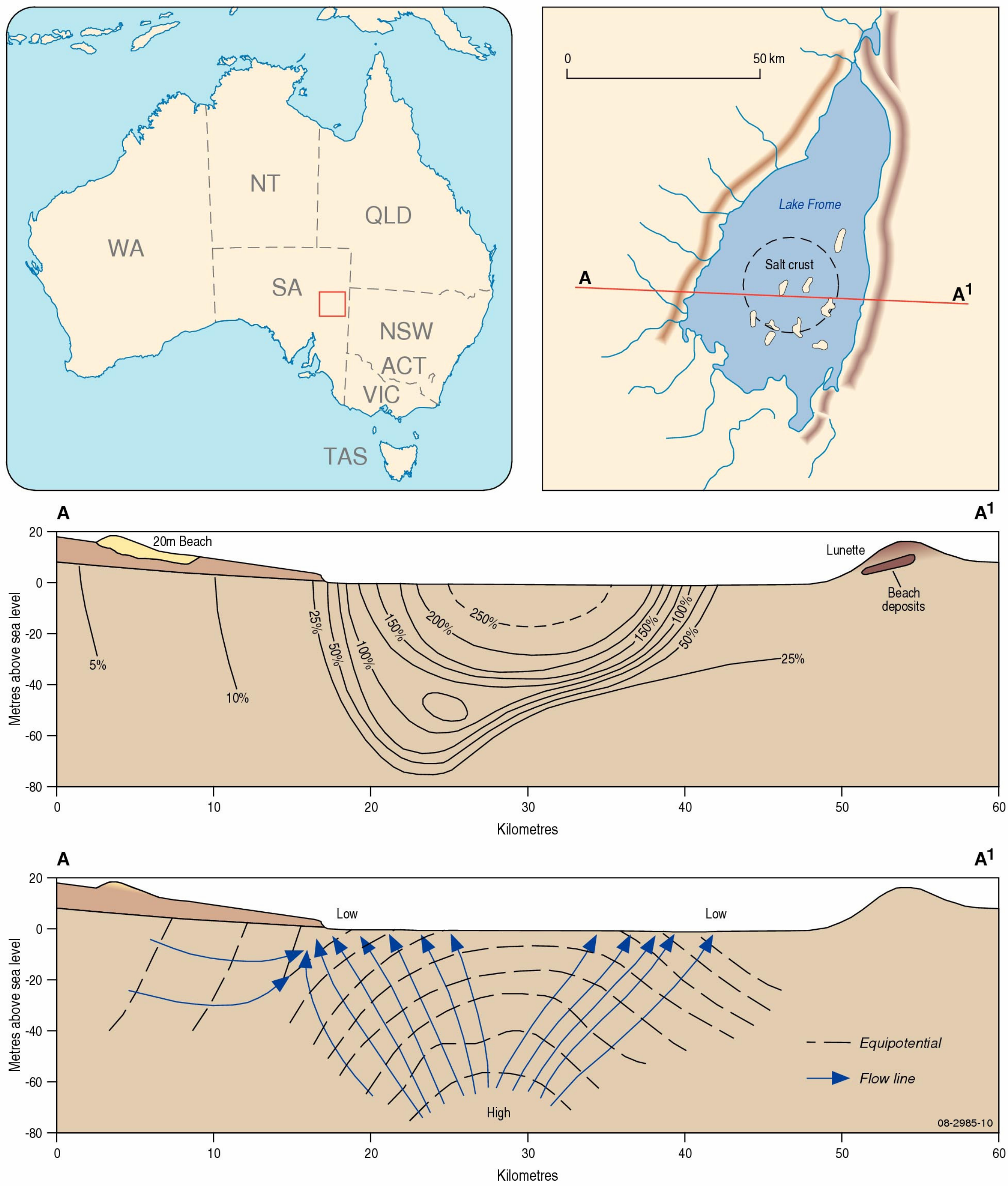


__Figure 2.7:__ Cross-section of Lake Frome illustrating the relationship between the surface salt crust and the structure of the underlying brine pool. The equipotential isolines indicate how the surface high-density brine pool refracts groundwater discharge flow away from the halite salt-crust zone towards the playa margins. Figure is modified from Bowler (1986) (Figure 4).

Macumber (1991) demonstrated that groundwater in the Parilla Sand aquifer at Lake Tyrrell is in metastable equilibrium, whereby the combination of an evaporative pumping-induced groundwater divide and Ghyben-Herzberg interface has closed-out seepage from the lake and down-gradient throughflow of regional groundwater. However, small changes in the water budget are capable of producing enhanced groundwater throughflow and out-seepage. It is very likely that evaporative pumping at playa discharge locations within palaeovalley groundwater systems can produce similar disruptions to groundwater throughflow in the palaeochannel aquifer. For example, in the eastern Yilgarn the calculation that playa discharge at Lake Yindarlgooda represents 96% of Roe Palaeodrainage throughflow, as discussed in Section 4.9.2.1 (Turner et al., 1994; Commander et al., 1992), indicates the existence of a significant blockage to groundwater throughflow. As Macumber (1991) argued for Lake Tyrrell, the lack of significant salt accumulation or salt crust at Lake Yindarlgooda indicates that the present situation is metastable and that significant groundwater throughflow (and salt flushing) has occurred in the past. Although the altitude (relative to the playa) of a watertable divide on the down-basin side of a playa is one of the most important controls over the continuity of groundwater throughflow, Macumber, (1991) lists other important factors such as:

- The position and geometry of aquifers beneath the lake;
- The ratios of vertical to horizontal hydraulic conductivities beneath the lake; and
- The water depth in the lake.

Bowler (1986) pointed out that highly soluble salts, such as halite, are not preserved in playa sediments until the underlying groundwater has evolved by reflux to near saturation levels (for those salts involved). This clearly seems to be the case for the majority of palaeovalley playas which only have thin discontinuous and/or ephemeral efflorescent deposits of halite and other highly soluble salts. Because most are not permanently closed to groundwater these palaeovalley playas do not have salinity levels which are sufficiently close to halite saturation to allow for the preservation of substantial quantities of soluble salts (as occurs, for example, in numerous salt lakes in the US and Middle East; Rosen, 1994).

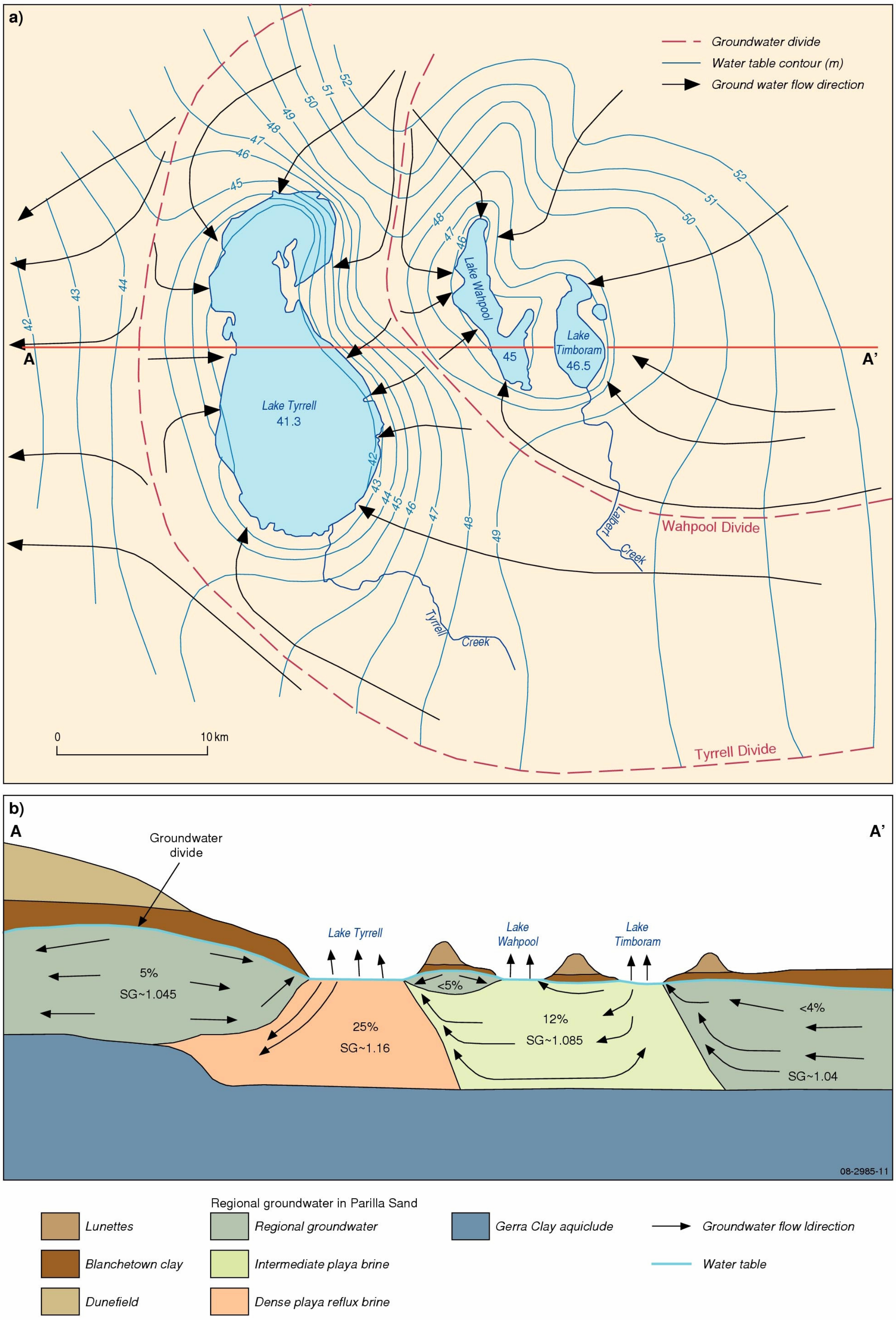

a)
Groundwater divide
Water table contour (m)
Ground water flow direction
A
A'
Lake Tyrrell
41.3
Lake Wahpool
45
Lake Timboram
46.5
Wahpool Divide
Tyrrell Divide
Tyrrell Creek
Lalbert Creek
0
10 km
b)
A
A'
Groundwater divide
Lake Tyrrell
Lake Wahpool
Lake Timboram
5%
SG~1.045
25%
SG~1.16
<5%
12%
SG~1.085
<4%
SG~1.04
08-2985-11
Regional groundwater in Parilla Sand
Lunettes
Blanchetown clay
Dunefield
Regional groundwater
Intermediate playa brine
Dense playa reflux brine
Gerra Clay aquiclude
Groundwater flow ldirection
Water table

Figure 2.8: (A). *Potentiometric surface and groundwater flow lines for the Parilla Sand aquifer in Victoria's Tyrrell Basin. The water table contours are strongly affected by the three discharge lakes, Tyrrell, Wahpool and Timboram. The floor of each lake intersects the water table. The closed contours around Lake Tyrrell and Lake Wahpool indicate groundwater inflow from all directions, whereas Lake Timboram (without similar contour closure) only receives inflow from the east. The groundwater flowlines demonstrate that regional groundwater flow only enters Lake Tyrrell from within the Tyrrell groundwater divide, excluding groundwater within the Wahpool divide which is captured by Lakes Timboram and Wahpool. However, groundwater underflow passes from the Wahpool–Timboram system to Lake Tyrrell. Macumber (1991) estimated that this process contributes about 33% of the Wahpool–Timboram inflow to Lake Tyrrell.*
(B). *East–west cross-section of the Tyrrell Basin showing groundwater flow and salinity variations of the regional Parilla Sand aquifer (3,000–5,000 mg/L TDS), the Lakes Timboram–Wahpool reflux brine pool (9,000–12,500 mg/L TDS), and the Lake Tyrrell reflux brine pool (20,000–29,000 mg/L TDS). Groundwater underflow from the Lakes Wahpool–Timboram system to Lake Tyrrell is also indicated. Figure is modified from Macumber (1991).*

3. Characteristics of Arid Zone Palaeovalley Groundwater Resources

As detailed in the regional descriptions of palaeovalley characteristics and stratigraphic sequences (Section 2.5), there is general consistency in the nature and age of palaeovalley sedimentary infill across the arid zone. The existence of calcrete, which is a major component of many palaeodrainage networks, but absent from others, is the most significant exception. As explained in Section 2.8 and 4.2, palaeovalley groundwater characteristics are a result of Quaternary landscape processes and will vary according to Quaternary climatic controls as well as aquifer characteristics, which reflect stratigraphic architecture and post-depositional modification. Thus it is likely that the nature and characteristics of palaeovalley groundwater systems will be more regionally variable than the infilling sediment sequences, particularly as calcrete deposits (the most widely variable stratigraphic element) are commonly significant palaeovalley aquifers.

There are many general characteristics however which are common to most palaeovalley groundwater systems. These include:

- Recharge rates are believed to be universally low and involve a complex variety of sources which are generally poorly understood or quantified;
- Storage capacity is high compared to other relatively shallow and easily accessible aquifers, particularly in trunk palaeochannel sediments, but is poorly quantified in most regions;
- The efficacy of mid- to long-distance throughflow and the balance between throughflow and within-palaeovalley playa evaporative discharge is extremely poorly understood or quantified;
- Palaeovalley groundwater salinity is generally high, particularly in trunk palaeochannel aquifers;
- Lower salinity groundwater preferentially occurs in tributary palaeovalleys and calcrete aquifers;
- Data demonstrating the impact of significant groundwater extraction from palaeovalley borefields is only available from the Goldfields area of the eastern Yilgarn, with some newly emerging data from the Tanami/Granites region (both for ongoing mining operations); and
- Organisms which reside in groundwater (**stygofauna**) are an emerging research topic with increasing evidence of extraordinary levels of taxonomic diversity and endemism, especially in palaeovalley calcrete aquifers. Biodiversity conservation issues involving stygofauna will undoubtedly become an increasingly important consideration for palaeovalley groundwater exploitation in the future.

3.1. RECHARGE

The main palaeovalley aquifers are the predominantly confined palaeochannel sand and gravel facies, which lie in the deepest parts of the infill sequence, and the generally more surficial and unconfined calcrete deposits. However, other locally important aquifers exist, such as post-Eocene unconfined or semi-confined fluvial sediments in central Australian palaeovalleys and Cenozoic basins. Direct recharge is generally regarded as minor in the arid zone (Lerner et al., 1990). The Eocene palaeochannel aquifers are generally confined laterally and below by weathered bedrock and above by Oligo-Miocene fine-grained and dominantly lacustrine sediments of the palaeovalley infill sequence (upper unit). The upper lacustrine unit is generally ubiquitous and covers a wider portion of the palaeovalley than the underlying palaeochannel facies, thereby preventing direct rainfall recharge of the palaeochannel aquifer. Commander et al. (1992) demonstrated that the fine-grained upper unit is generally absent from the uppermost palaeovalley tracts of the Roe Palaeovalley near

Kalgoorlie, and direct recharge from rainfall to the palaeochannel aquifer occurs there. There is insufficient stratigraphic information available from the upper palaeovalley tracts of most arid zone regions to say if these observations from the Roe Palaeovalley are unique or more widely applicable. This is clearly a potential topic for future investigation. Even if there is widespread absence of the upper confining unit from the upper reaches of most palaeovalleys, unconfined palaeochannel facies aquifers almost certainly form a small proportion of the total palaeovalley length and direct recharge from rainfall is probably a correspondingly small proportion of total aquifer recharge. Recharge is likely to be dominated by slow vertical and lateral leakage from surrounding saturated weathered bedrock and the overlying fine-grained upper unit. These, in turn, are recharged directly from rainfall but at very low rates in the modern climate regime. Commander et al. (1992) argued that a number of factors combined to cause generally low recharge rates in the Roe Palaeovalley, including:

- Low magnitude and intensity of rainfall;
- High E/P (evaporation/precipitation) ratio;
- Relatively thick vegetation cover;
- Clayey soils; and
- Low permeability of both the weathered/fractured bedrock and the upper fine-grained palaeovalley unit.

Commander et al. (1992) were unable to quantify the recharge rate but subsequent estimates based on modelling and isotopic dating methods in a portion of the Roe Palaeovalley by Turner et al. (1994) confirmed that recharge rates are extremely slow. Commander et al. (1994) analysed ^{36}Cl and ^{14}C isotopes from groundwater in the Roe and Rebecca Palaeovalley systems and determined chloride residence times >100,000 years and a hydraulic regime of low recharge, continual concentration of salts by playa evaporation, groundwater mixing and circulation between playas and underlying palaeochannel sand aquifers.

Commander et al. (1992) suggested that widespread and rapid clearing of trees in the upper catchment of the Roe Palaeovalley after underground mining started at Kalgoorlie (early 1900's) should have resulted in enhanced recharge. However, they were unable to determine evidence of this in the palaeovalley systems. Implicit in the prediction of a recharge response to clearing by Commander et al. (1992) is the recognition that changing the environmental boundary conditions (e.g., climate or vegetation) will potentially have a direct effect on recharge, e.g., either enhancing or retarding recharge rates. Clearly climate and vegetation have changed significantly at Quaternary glacial/interglacial timescales and recharge is thus likely to have been episodic (10^4–10^5 years). Evidence for the reality of long-term (10^4–10^5 years) episodic recharge is provided by Cresswell et al. (1999) from ^{36}Cl dating of palaeovalley groundwater in the south-western Northern Territory, where recharge events were identified at 80–100 ka and in the early Holocene, in agreement with long-term records of monsoonal surface water hydrology (Magee, 2007) and monsoon-driven recharge to the Great Artesian Basin (Radke et al., 2000; Prescott and Habermehl, 2008).

Where present, the palaeovalley calcrete aquifers are unconfined and usually exposed at the ground surface or shallowly buried by unconsolidated permeable surficial sediment. They typically occur over a significant areal extent of the palaeovalley. These characteristics ensure that they are much more amenable to direct rainfall recharge than the palaeochannel aquifers. Chapman (1962) and Sanders (1972) have provided recharge estimates for Wiluna Palaeovalley calcrete aquifers, from climate/runoff parameters, which suggest significantly higher recharge estimates than for palaeochannel sand aquifers. It is likely that recharge estimates by such techniques will be more reliable for calcrete aquifers than for palaeochannel aquifers, given the likelihood of widespread direct rainfall recharge to near-surface calcrete deposits.

Most recharge estimates for palaeochannel and calcrete palaeovalley aquifers have been based on assumed rates of rainfall infiltration efficiency at specific intensities and magnitudes (Domahidy, 1990; Tewksbury and Dodds, 1997). The effective contribution of overland flow resulting from precipitation over topographically higher areas adjacent to palaeovalley tracts is the greatest uncertainty of this method. At best these can be regarded as educated guesses. In most cases the derived modern recharge rates are realistically very low, but some are overly optimistic, e.g., Domahidy (1990). There are some more rigorous numeric recharge estimates based on modelling and isotopic dating of groundwater by ^{36}Cl and ^{14}C now available for palaeovalley aquifers (Turner et al., 1993, 1994; Cresswell et al., 1999, Harrington et al., 1999, 2002). It is highly desirable that similar quantitative methods be extended widely across the arid zone to enhance our understanding of the magnitude and episodic history of palaeovalley groundwater recharge. The importance of episodic very high-magnitude events with long return periods makes quantitative assessment of average recharge rates extremely difficult. For instance watertable levels in the Ti-Tree Basin are still adjusting to recharge from the extreme rainfall event of 1974 (Harrington et al., 2002) and even though the recharge estimates of Domahidy (1990) are optimistic as average values, there is no doubt that significant recharge to Tanami palaeovalley calcrete aquifers has occurred during high-magnitude monsoon events (J. Wischusen, pers. comm. 2008).

3.2. STORAGE

In arid zone regions where palaeovalleys occur, deep bedrock aquifers with abundant groundwater reserves are likely to be restricted to the Eromanga, Officer, Amadeus and Canning Basins. With the exception of the Amadeus Basin, particularly the Mereenie Sandstone, there has been little exploration or exploitation of these resources. However, many decades of seismic surveying and well drilling for petroleum exploration could provide basic information about stratigraphic architecture and aquifer characteristics in those basins. In terms of shallow, readily accessible groundwater resources over the project study area, three main aquifer systems occur:

- Fractured and weathered bedrock;
- Surficial alluvial, colluvial and aeolian deposits; and
- Palaeovalley calcrete and palaeochannel sand and gravel facies.

The bedrock and surficial sediment aquifers are significantly more widespread than the palaeovalley aquifers, but are generally less-effective at transmitting or storing groundwater. Thus palaeovalley aquifers have the highest potential for effective groundwater extraction for all but the highest volume requirements; storage reserves are however very poorly quantified for most arid regions.

The Eocene palaeochannel facies were generally deposited in braided river environments with multiple channels. There were numerous cut and fill episodes and widespread deposition of lignite-bearing facies and clay beds in valley lakes and swamps. De Broekert (2002) provided the most complete descriptions of the stratigraphic architecture and facies complexity of these palaeovalley sediments. The most deeply incised palaeovalley section (which contains the palaeochannel facies) is sinuous and its width can vary significantly along-strike. Additionally, palaeochannel sediments have been variably modified by post-depositional weathering processes and duricrust formation. These palaeochannel aquifer characteristics reflect the stratigraphic architecture dominated by generally small and irregular individual bedforms, though down-valley connectivity and groundwater transmission between bedforms is generally good. The palaeovalley calcrete aquifers have been precipitated from shallow migrating groundwater, and may commonly replace the upper fine-grained palaeovalley infill unit. Calcrete characteristics such as mineralogy, thickness, lateral extent, degree of cementation, original porosity and secondary porosity (solution weathering) can be highly variable as they depend on complex chemical reactions between shallow groundwater and the host sediments.

The nature and volume of both palaeochannel and calcrete palaeovalley aquifers can be highly variable along the length of the palaeovalley. Consequently, the groundwater resources can only be accurately determined by multiple drilling transects oriented across-strike of the palaeovalley, thereby allowing quantification of the aquifer cross-sectional area and various storage parameters. Data of this nature, sufficient to accurately quantify palaeovalley groundwater storage, is restricted to some palaeovalleys in the eastern Yilgarn region, particularly the Roe palaeovalley (Commander et al., 1992; Kern and Commander, 1993; Johnson et al., 1999). Less reliable storage estimates are available from more limited drilling and pump testing (of water-bores) in the Garford Palaeovalley aquifer in the Gawler Craton (Martin et al., 1998), and from the Tanami/Granites region of the North Australian Craton (Domahidy, 1990). As explained in Section 4.1.2., the major source of recharge to the palaeochannel aquifer is believed to be derived from lateral slow leakage from less effective aquifers of the underlying and adjacent bedrock and overlying, more widespread upper palaeovalley unit. Both Commander et al. (1992) and Turner et al. (1993) demonstrated that drawdown from groundwater extraction in the Roe palaeochannel aquifer enhanced this lateral recharge process. This observation has important implications for the estimation of exploitable reserves of palaeovalley groundwater, particularly for the main palaeochannel aquifers.

Because of the marked similarity of valley-fill sediments, aquifer characteristics and groundwater systems in palaeovalleys across the study region, the quantitative estimates of groundwater storage derived for the Roe palaeovalley are likely to be broadly indicative of other palaeovalleys. However, the regional differences which do occur and the climate gradients (magnitude and seasonality of precipitation) across the project study region suggest that detailed quantitative determinations of storage should be obtained from each demonstration area. Also pertinent are observations by P. Commander (pers. comm. 2008) that unexploited palaeochannel aquifers in the eastern Yilgarn are effectively at, or very close to, full storage capacity and much current recharge is probably rejected. In such circumstance it will be important to quantify how quickly an aquifer can change to effective recharge following reduction in storage due to groundwater abstraction.

3.3. THROUGHFLOW

Arid zone palaeovalleys are mostly defunct surface water systems but the existence or efficacy of mid- to long-distance groundwater throughflow is clearly a major uncertainty. Some indications of long distance throughflow appear in the literature, including suggestions that eastern Yilgarn palaeovalleys may discharge into Eocene near-shore marine facies underlying the middle Cenozoic Eucla Basin limestones of the Great Australian Bight. Commander (1991) suggested that palaeovalley aquifer throughflow was indicated by much higher groundwater salinities in the marginal Loongara Sandstone and Hampton Sandstone compared with lower salinity groundwater in the central Eucla Basin.

The long-term general tectonic stability of the continent has mostly preserved original down-slope gradients in palaeovalleys and these continuous, though low, gradients should provide sufficient hydraulic head to maintain slow but effective throughflow. However, there are also numerous documented examples of local tectonic disruption and reversal of original gradients (Beard, 1973, 1998, 1999, 2000, 2002, 2003; Bunting et al., 1974; van der Graaff et al. 1977; Sandiford et al.,

2007) which undoubtedly disrupt or occlude throughflow. Additional barriers to effective throughflow can arise from:

- Topographically high, resistant impermeable bedrock features, such as greenstone belts and dykes, which are intersected by palaeovalleys;
- Significantly reduced aquifer cross-sectional area due to complex channel facies architecture;
- Reduced permeability and porosity due to precipitation of secondary deposits; and
- Groundwater divides formed down-valley from evaporative discharge playas due to development of reflux brines (Section 2.8.1).

With low gradients and multiple opportunities for occlusion of throughflow, it is likely that many palaeochannel aquifers have stagnant groundwater reserves which will be forced towards the surface by the hydraulic head, leading to evaporative discharge and playa development. Continued playa evaporation and evolution of reflux brines can enhance occlusion of throughflow and become self-perpetuating, until critical boundary conditions are altered. Salinity stratification in palaeovalley aquifers, as reported from the Roe Palaeodrainage (Commander et al., 1992) and the Raeside and Carey Palaeodrainages (Johnson et al., 1999), is indicative of relative stagnation and occlusion of throughflow.

Accordingly, the different categories of palaeovalley playas can be assumed to imply various degrees of effective or occluded throughflow (Section 2.8.1). Very large and irregular palaeovalley playas, such as Lake MacKay and Lake Disappointment, clearly indicate a long-term absence of down-valley throughflow and consequent development of a large, hypersaline reflux brine pool. This implies major prolonged tectonic disruption to the down-valley gradient which has been documented for Lake Disappointment (Beard, 2005) but is unresolved for Lake MacKay (Beard, 1973, 2003; Sandiford et al., 2007). In such cases there is no possibility of groundwater throughflow along the former palaeovalley without effective reversal of the mechanism of tectonic occlusion. Palaeovalleys with common large or elongate playas along their tracts, such as those of the eastern Yilgarn, indicate severely but not completely occluded throughflow. Aquifer blockage is likely to be due to multiple causes including all of those listed in Section 2.8.1, with lithological barriers and structural features particularly important in the Yilgarn (Salama et al., 1992, 1993; Clarke et al., 1998). Reflux brine pools in the large playas developed in these palaeovalleys undoubtedly add to the occlusion of groundwater throughflow. As Commander et al. (1992) and Turner et al. (1993) demonstrated in the Roe Palaeodrainage, there is presently little effective throughflow in these Yilgarn palaeovalley systems; however, the potential for enhanced throughflow could be re-established where aquifer barriers are partial and climatic and hydrologic boundary conditions change. Palaeovalleys with fewer and smaller playas are likely to have the most effective long-distance groundwater throughflow. However, palaeochannel aquifers in these systems may have lower recharge rates and storage capacities, with correspondingly reduced potential for evaporative discharge and playa development. The degree of throughflow in palaeochannel aquifers of palaeovalleys with few and small playas should be investigated further as part of this investigation.

3.4. DISCHARGE

Groundwater discharge from palaeovalley aquifers is likely to involve four main mechanisms:

- Throughflow to successively higher order palaeovalleys eventually discharging to laterally connecting shoreline or marine near-shore facies sediments;
- Evaporative discharge from playas or salt lakes within the palaeovalleys;

- Transpiration by plants where roots can access the watertable (transpiration is often considered in combination with evaporation as evapotranspiration); and
- Slow lateral leakage may occur to underlying, lateral or overlying confining bedrock or palaeovalley stratigraphic units.

As implied above, there is a complex inter-relationship between palaeovalley groundwater throughflow, evaporative playa discharge and groundwater salinity. Throughflow and playa discharge are complementary; where playas are large or abundant, playa evaporation will locally be the dominant discharge mechanism. This was demonstrated at Lake Yindarlgooda in the Roe Palaeodrainage by Commander et al. (1992) and Turner et al. (1993). Commander et al. (1992) attempted to quantify evaporative discharge from Lake Yindarlgooda, but assumed relatively high evaporation rates based on pan evaporation measurements. Net evaporation from playas is controlled by complexities of flow direction focussing or deflection by reflux brine pools and surface processes such as sealing by efflorescent salt crusts. Experimentally derived and field-measured values are much lower than pan evaporation values (Allison and Barnes, 1985; Ullman, 1985; Schmid, 1985; Jacobson and Jankowski, 1989; Chen, 1992). It is important that evaporative discharge rates from palaeovalley playas be determined quantitatively across the study region by methods such as chemical and isotopic profiling.

Slow lateral leakage from palaeovalley aquifers undoubtedly occurs along extensive valley tracts at variable rates according to the nature of the hydraulic connectivity between the aquifer and bounding units, and the degree of saturation of those units relative to the palaeochannel aquifer. Upward leakage is ultimately discharged as evapotranspiration at the surface and it is likely that slow leakage will be the dominant discharge mechanism from palaeovalley aquifers because of their potentially large areal extents. No quantitative estimates or measurements of slow leakage were located in the scientific literature for this review.

3.5. GROUNDWATER QUALITY

Palaeovalley groundwater salinity levels are generally high as a result of long residence times and evaporative concentration due to the significant contribution of playa evaporation to groundwater discharge. This is particularly true for the palaeochannel aquifers in higher order and trunk palaeovalleys where playas generally form. These higher-order palaeovalleys contain the greatest aquifer volume and consequently the largest groundwater reserves. For this reason palaeovalley groundwater tends to be dominantly a saline to hypersaline resource. Despite this situation, palaeovalley groundwater should not be universally dismissed as suitable only for limited use, such as supplying processing water for mining operations. As outlined in Section 4.1.1, the upper, lower-order palaeochannel aquifers and the majority of calcrete aquifers are believed to be directly recharged by rainfall and will therefore contain a lower salinity groundwater resource. These have the potential to provide potable water supplies. For instance, Johnson et al. (1999) reported salinity values of 1,000–3,000 mg/L (which is at or just above potable supply limits) from the upper tributaries of the Raeside and Carey Palaeodrainage networks.

Although many trunk palaeovalley reaches are predisposed to contain higher salinity groundwater, some palaeovalley systems are the focus of the freshest groundwater resources within specific catchments. For example, in the Cenozoic basins adjacent to upland ranges in central Australia, palaeovalleys contain the freshest (often potable) groundwater, whereas adjacent palaeo-interfluve aquifers contain more saline groundwaters. In these settings, where episodic recharge occurs in the contemporary climate regime, the palaeovalleys are the main conduits for recharge derived from runoff sourced from the adjacent bedrock ranges. They function as discharge zones only in their lowermost reaches. Groundwater in shallow palaeovalleys have young ^{14}C ages and high bicarbonate to chlorine (HCO_3/Cl) ratios whereas adjacent palaeo-interfluve aquifers contain more evolved water, with older ^{14}C ages and relatively low HCO_3/Cl ratios. The palaeo-interfluves are not as readily flushed, being typically more clay-rich, and thus store salt for longer periods – groundwater residence times may be > 10,000 years (English 2002; 2004). In palaeovalley systems in the Western Australian Wheatbelt, saline to hypersaline groundwater is common where discharge occurs in broad flat areas. However, small zones of fresh groundwater also exist, and fresh groundwater lenses can occur commonly in aeolian cover sediments (R. George, West Australia Department of Agriculture and Food, pers. comm. 2007).

Calcrete aquifers and palaeochannel aquifers in lower-order and tributary palaeovalleys should be targeted initially for potential supplies of lower salinity groundwater. When considering water supplies for remote communities it is important to consider the potential of palaeovalley groundwater in the context of possible alternatives. Deep groundwater resources are currently under-explored in most areas of the arid zone, although they are relatively more expensive to access than shallow groundwater. In comparison, shallow surficial and bedrock aquifers are widely available and these are currently exploited in some areas, however many also have borderline salinity levels and may contain specific ionic contents (e.g., nitrate, sulfate, fluorine) which significantly exceed recommended World Health Organisation limits and are unattractive due to water hardness. Thus, groundwater resources of surficial and bedrock aquifers are commonly only of slightly better quality than the freshest groundwater available in palaeovalley aquifers, and these are likely to contain lower overall reserves and have lower production capacities. Though desalination is relatively expensive and energy intensive the technology is constantly improving. Thus, it is likely that desalination of palaeovalley groundwater represents the best long-term option for viable quantities of potable drinking water for many remote communities (Dodds, 1997).

One clear advantage of the relatively abundant but highly saline groundwater in the higher-order palaeovalleys is that they represent a viable source of mineral/ore processing water for remote-area mines. Although the elevated salinity and other palaeovalley groundwater characteristics, such as pH, are often less than optimal for ore-processing, the savings in infrastructure costs required to access more suitable water can often be considerable and easily exceed the cost of water pre-treatment. Accessing a water source which is not suitable for other users can also enable mining companies to avoid competing for limited sources of higher-quality water.

3.5.1. High Nitrate Contents

In addition to the problems associated with elevated salinity levels in groundwater in the Australian arid zone (including palaeovalley aquifers) significant health issues exist around the potentially toxic concentrations of specific ions in groundwater, including radiogenic isotopes, fluoride, boron, and nitrate. Nitrate is probably the most widespread of these toxic elements in Australia and often adversely affects groundwater which may otherwise be potable.

The origin of high nitrate contents and the assessment of safe consumption levels are complex issues. Elevated nitrate levels in groundwater usually result from human activities such as overuse of chemical fertilizers and improper disposal of human and animal wastes. Fertilizers and wastes are sources of nitrogen-containing compounds which are converted to nitrates in the soil. Nitrates are extremely soluble in water and can move easily through soil into groundwater (McCasland et al., 2008). However, this is highly unlikely in the relatively undisturbed (non-agricultural) and lowly populated landscapes of the Musgrave Province and Officer Basin region. Nitrates in this region are derived from the biosphere, probably from a combination of plants fixing atmospheric nitrogen and the decomposition of plant and animal waste (Tewksbury and Dodds, 1997), including termite mound bacterial action (Fitzgerald et al., 2000). A detailed study of the Uluru region in central Australia by Barnes et al. (1992) established that termite activity was the major nitrate source, with a significant contribution also from cyanobacterial soil crusts.

Nitrite (NO_2), which results from reduction of nitrate, is actually the main cause of health problems when consumed in sufficient quantities. Short-term exposure to drinking water with unsafe nitrate levels is primarily a potential health problem for infants. Babies consume large quantities of water relative to their body weight and their immature digestive systems are more likely than adult digestive tracts to allow the reduction of nitrate to nitrite. In particular, the presence of nitrite in the digestive tract of newborns can lead to a disease called methaemoglobinaemia, which is the most significant health problem associated with nitrate in drinking water. When nitrite is present, haemoglobin can be converted to methaemoglobin, which cannot carry oxygen. In adults, enzymes in the blood continually convert methaemoglobin back to haemoglobin, which maintains methaemoglobin levels of less than 1% in the body. However, newborn infants have lower levels of these blood enzymes, and may have higher methaemoglobin levels of ~1–2%. Anything above that level is considered methaemoglobinaemia. Table 3.1 summarises the effects of various levels of methaemoglobin in the blood (McCasland et al., 2008).

Table 3.1: Methaemoglobin levels in human blood and associated physiological effects (from McCasland et al., 2008).

METHAEMOGLOBIN LEVELS (%)	SYMPTOMS
<1	Normal adult levels
1–2	Normal infant levels
2–10	Few consistent symptoms
10–20	Cyanosis – blue mucous membranes, possible dietary and respiratory problems
20–50	Anoxia
50–70	Brain damage and/or death

Methaemoglobinaemia can be readily reversed, although permanent tissue damage may result from anoxia. The condition can be prevented by restricting the consumption of nitrite and nitrate in water and food and by limiting the opportunities for bacteria to reduce nitrate in food. The World Health Organisation standard is 45 mg/L NO_3 (equivalent to 10 mg/L N in NO_3) but adults tolerate up to 100 mg/L without adverse affects, except for individuals with exposure to antioxidant medications and chemicals or other conditions that may inhibit the body's ability to reconvert methemoglobin to haemoglobin (including pregnancy and certain rare diseases) (McCasland et al., 2008).

3.6. GROUNDWATER ABSTRACTION

Data on the aquifer response associated with significant abstraction of palaeovalley groundwater resources are only available from a number of mine processing borefields in the Roe Palaeodrainage (Commander et al., 1992; Johnson, 2007). Commander et al. (1992) and Turner et al. (1993) demonstrated that rates of abstraction for mine processing water in the Roe Palaeodrainage were not sustainable with respect to down-valley recharge, even though the recharge rate was poorly quantified. However, both studies drew attention to the unquantified impact of enhanced lateral recharge induced by significant extraction of groundwater from the palaeochannel aquifer. This was further investigated by Turner et al. (1996) who determined that their previous estimate of enhanced groundwater resources from aquitard leakage was overestimated and concluded that palaeovalley groundwater extraction for mine processing in the Roe Palaeovalley was actually unsustainable. They predicted ongoing water-level decline resulting in storage depletion sometime from 2012–2022. This pessimistic outlook, and potential limit to mining operations, led to groundwater allocation on a managed depletion basis and to detailed long-term monitoring of water-level response to abstraction in the Roe Palaeovalley borefields (Johnson, 2007). As explained in Section 4.9.2.4, the borefield monitoring program demonstrated that initial water-level decline with abstraction was followed by steady-state conditions that indicated a sustainable balance between abstraction and groundwater inflow. Water-level recovery following reduced abstraction confirmed this conclusion. Johnson (2007) concluded that weathered bedrock aquifers adjacent to the palaeovalley received recharge from high-magnitude rainfall and playa flooding events. Lateral leakage inflow from weathered bedrock to the palaeochannel aquifer was further enhanced by depressurisation induced by abstraction. Johnson concluded that the evidence indicated a total of 35 GL per year of sustainable groundwater resources for the 400 kilometre strike-length of the Roe Palaeovalley and recommended re-allocation of the groundwater resources on that basis.

Quantification of enhanced indirect lateral recharge in other palaeovalleys, as a response to abstraction, will be important for an accurate resource estimation and assessment of the sustainability of groundwater abstraction.

In the Curnamona Province, the Oligo-Miocene Beverley Palaeochannel aquifer is incised into Namba Formation Alpha Mudstone, rather than weathered bedrock, and is completely confined in all directions (Figure 3.1 and Figure 3.2). In addition, down-valley throughflow from recharge sources is limited and these factors combine to result in a stagnant groundwater system, despite the high transmissivity of the channel-sand aquifer. The hydrologic isolation of the aquifer is clearly evident in the rapid drawdown response and very slow recovery to pumping (Heathgate Resources, 1998). The Beverley Palaeochannel aquifer has no access to indirect recharge by lateral leakage, as occurs in the Roe Palaeochannel, as demonstrated by rapid and sustained storage depletion following abstraction.

3.7. STYGOFAUNA

Stygofauna is a general term for a taxonomically diverse group of animals, mostly invertebrates, which inhabit subterranean, groundwater-dependent ecosystems. These can vary from near-surface environments such as interstitial water in bedload sands and gravels of ephemeral streams to relatively deep groundwater systems in cavernous, weathered limestone or calcrete. Stygofauna have only been studied in detail in Australia in the past decade, and research into the array of environment types and geographic range has elucidated an ever-expanding species abundance and diversity (Humphreys and Harvey, 2001; Tomlinson and Boulton, 2008). Of most interest for palaeovalley studies is the widespread occurrence of stygofauna in calcrete aquifers within the upper trunk drainages of arid zone palaeovalley systems.

Humphreys (2001) summarised current knowledge of palaeovalley calcrete aquifer stygofauna particularly in the northern Yilgarn and Pilbara, where palaeovalley calcrete deposits are very extensive. These calcretes contain a diverse array of stygofauna, mainly various crustaceans but also including worms, molluscs and water beetles (Humphreys, 2001; Reeves et al., 2007). Most significantly, they demonstrate an extraordinarily high-degree of endemism within each calcrete region examined, which effectively means different palaeovalley systems contain unique stygofauna. Humphreys (2001) attributed this pattern of endemic fauna in each palaeovalley system to a combination of the long regional history above sea-level (at least since the Palaeozoic) and the downstream increase in salinity towards hypersaline groundwater (25,000–30,000 mg/L) at palaeovalley playas or salt lakes where evaporative discharge occurs. These zones of hypersaline groundwater preclude connection between stygofaunal communities in the fresh-to brackish upstream portions of each palaeovalley tributary, and the long periods of separation have resulted in development of the diverse range of species.

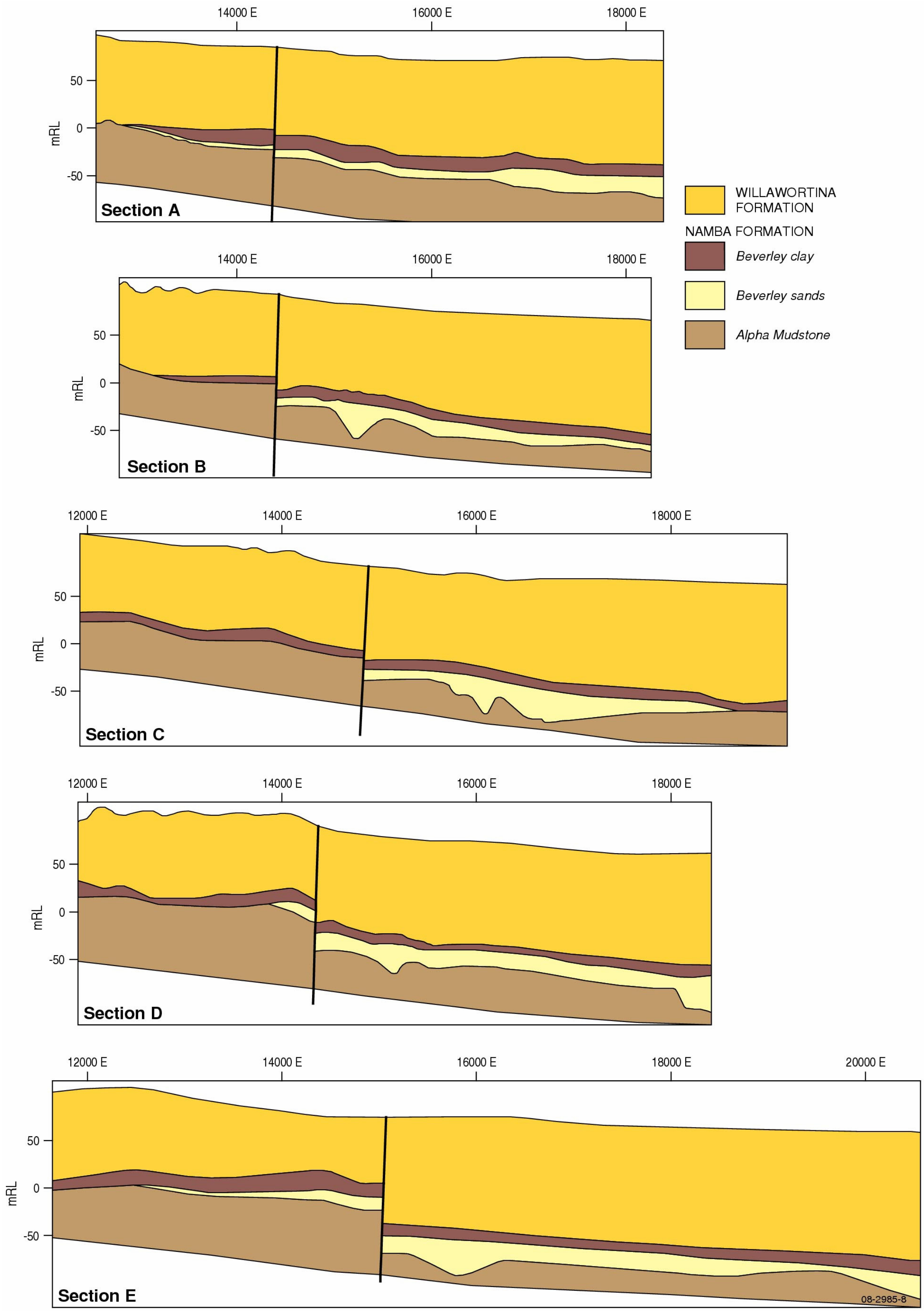


Figure 3.1: *Beverley Palaeovalley cross-sections showing the variable thickness and shape of the main palaeovalley infill sequence of the Namba Formation. The location of these interpreted cross-sections is shown in Figure 3.2. Figure is modified from Heathgate Resources (1998).*

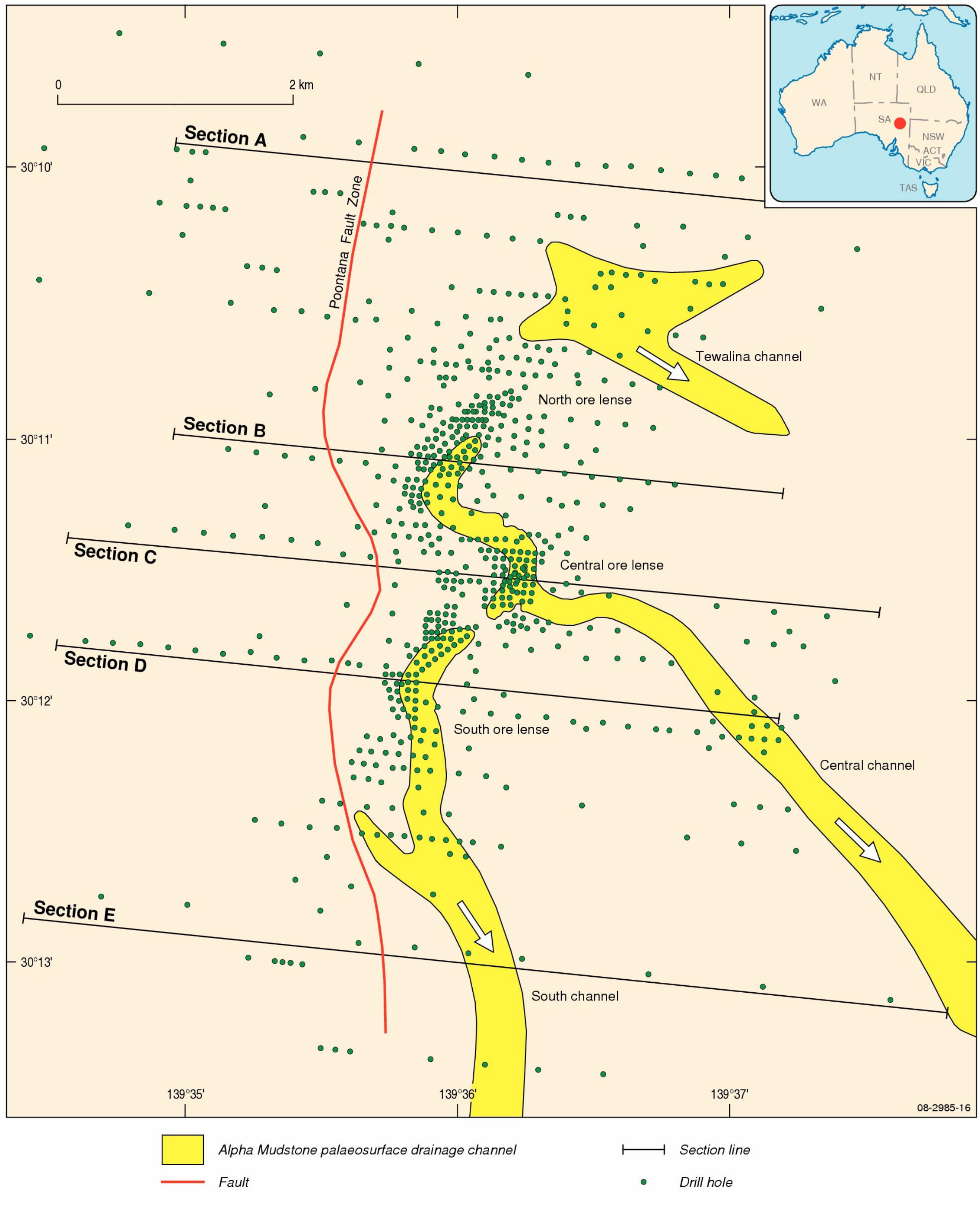


Figure 3.2: *Plan view of the Beverley uranium deposit highlighting the location and groundwater flow vectors of the main palaeochannels. Note the abundance of drilling data which has been used to generate a detailed understanding of the structure and stratigraphic architecture of the infill sediments. The five cross-section lines (A to E) shown here correspond to the sections in Figure 3.1. Figure is modified from Heathgate Resources (1998).*

The presence of abundant and diverse stygofaunal assemblages and more particularly the widespread existence of unique and endemic faunas in the headwaters of each palaeovalley tributary will undoubtedly have considerable future implications for the extraction or disturbance of palaeovalley groundwater (Tomlinson and Boulton, 2008). This situation will become more evident as research on stygofaunal communities extends more widely in geographic extent and environment types, and as the information about them becomes more widely known, in both the general and conservation communities. Already, legislation in most jurisdictions precludes causing the extinction of any taxonomic group. Extraction or disturbance (e.g., by mine de-watering) of palaeovalley calcrete aquifers may well have to conform with tight legislative regimes of environmental assessment and monitoring on biodiversity conservation grounds, which has generally not been applied to most groundwater use in the past.

4. Arid Zone Palaeovalley Regions and their Groundwater Resources

Australia's arid zone palaeovalleys cover a substantial portion of the continent and occur on a variety of landforms and geological settings. They also share many common morphologic, stratigraphic and groundwater characteristics. The Australian continent was uniformly wet when palaeovalleys were mostly incised during the Eocene, probably with a slight south-to-north temperature gradient (Langford et al., 1995). Since the Eocene the climate has become drier and environmental contrasts have increased, both from south-to-north and from the interior to the coast. This has resulted in the variable post-depositional evolution of many palaeovalleys across the arid zone, including the development of their groundwater systems.

This chapter provides an overview of palaeovalley stratigraphic sequences and groundwater resources from the major arid zone regions of Australia (Figure 4.1). In an arbitrarily chosen sequence, these areas include the:

- Curnamona Province;
- Lake Eyre Basin;
- Central Australian region;
- North Australian Craton (mainly the Tanami region);
- Canning Basin and Great Sandy Desert;
- Western and Eastern Yilgarn Craton;
- Western Eucla Basin margin, including the Gibson and Great Victoria Deserts (Officer Basin);
- Musgrave Province; and
- Eastern Eucla Basin and Gawler Craton.

4.1. CURNAMONA PROVINCE

The Curnamona Province (Crooks, 2005) is a 300 x 300 kilometre block of outcropping to shallowly buried basement rocks that have been stable since the Delamerian Orogeny, about 500 million years ago. The Curnamona Province extends from Olary, in the north-east of South Australia, to east of Broken Hill in New South Wales, and the terranes distinctive magnetic signature is also recognised to the north of Lake Frome (buried under surficial cover). Multiply deformed rocks of the Willyama Complex form most of the Curnamona Province, comprising a variable assemblage of Palaeoproterozoic to Mesoproterozoic sedimentary, volcanic and granitic rocks. The Curnamona Province is subdivided into the Broken Hill Domain, the Olary Domain, the Weekeroo Inlier, the Mt Painter Inlier, the Mt Babbage Inlier, and the Benagerie Ridge (Figure 4.2). Outcropping rocks of the Willyama Supergroup at Weekeroo, Mt Babbage and Mt Painter are inliers within the Neoproterozoic terrane, which elsewhere forms a younger sedimentary cover sequence along with Cambrian and Cenozoic rocks and sediments. Post-deformation volcanic and sedimentary rocks form a major basement high, the Benagerie Ridge, which separates Cambrian aged rocks of the Yalkalpo and Moorowie sub-basins. The Curnamona Province is of great metallogenic importance, hosting the Broken Hill silver-lead-zinc mine and many smaller deposits of similar style. Importantly for the Palaeovalley Groundwater Project, geophysical exploration datasets, including aeromagnetics, gravity and radiometrics, are available across much of the Curnamona Province which is otherwise covered by extensive surficial sediments.

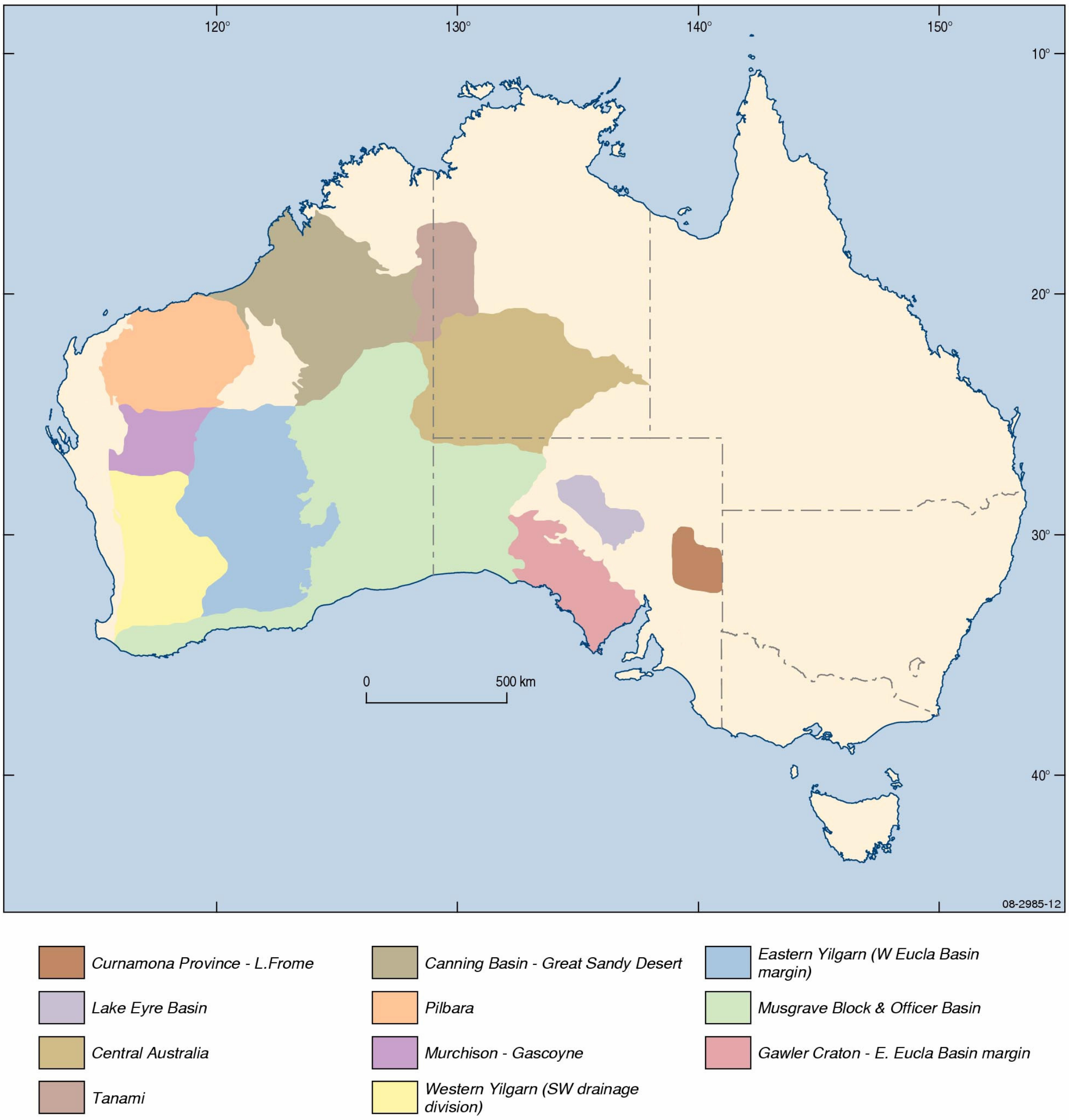


Figure 4.1: *Location map of the major arid to semi-arid regions of Australia which contain palaeovalley systems investigated as part of this literature review.*

An extensive network of river channels rising in the elevated Olary Domain and the Mt Babbage and Mt Painter Inliers carried sediments widely across the Curnamona Province during Palaeogene and Early Neogene times (Figure 4.3). These palaeovalley deposits host significant uranium mineralisation originally sourced from uranium-rich rocks in the Curnamona Province, forming economic accumulations at several sites including the Beverley and Honeymoon mines. Considerable uranium exploration has focussed on the palaeochannels around the margins of Lake Frome and, in combination with environmental impact assessments for Beverley (Heathgate Resources, 1998) and Honeymoon (Southern Cross Resources, 2000), have elucidated considerable information about the palaeovalley sediment sequences. Palaeovalley systems further up-basin towards the outcropping Olary Ranges have also been exploration foci, generally for secondary metalliferous or placer deposits.

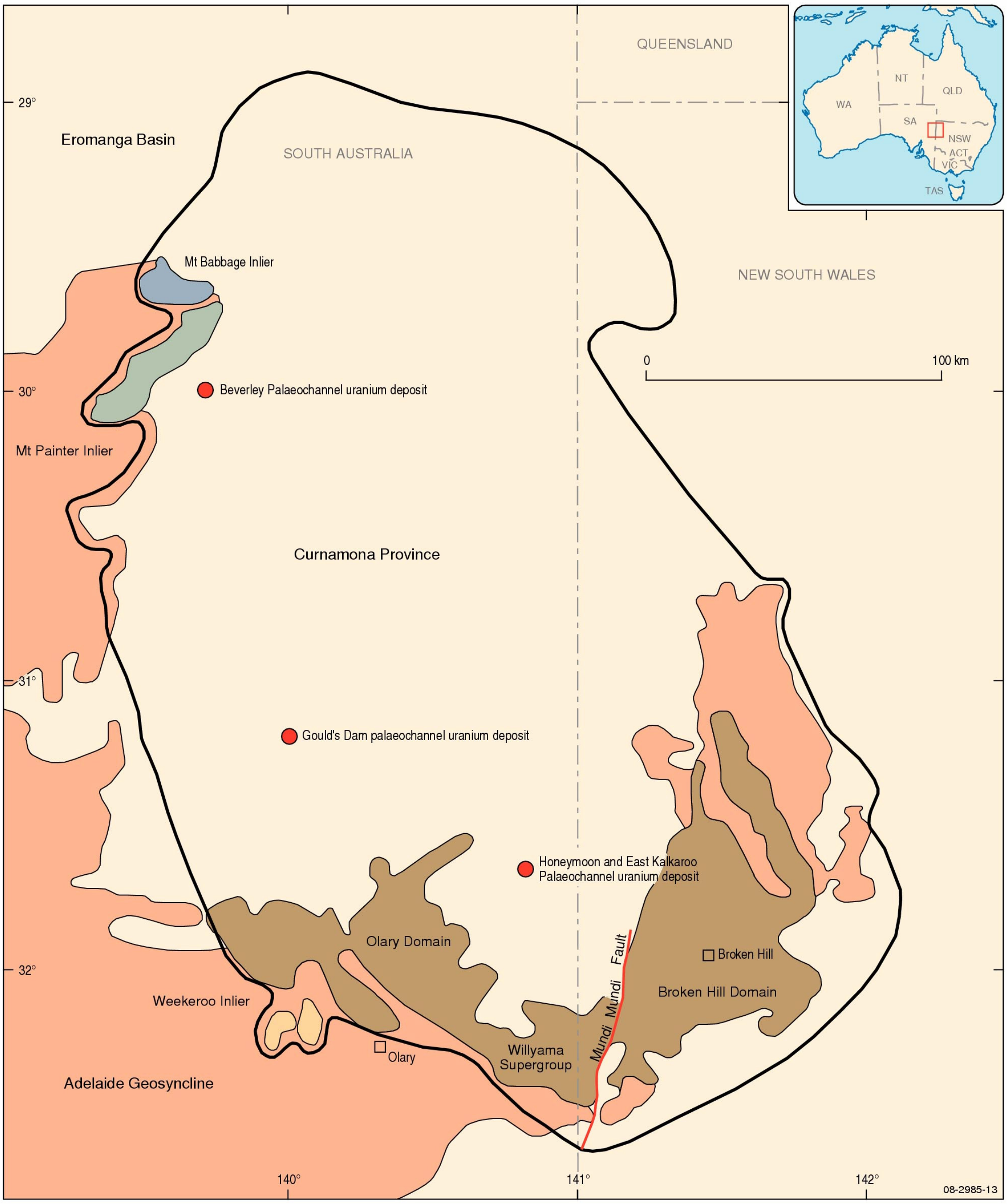


Figure 4.2: *Map of the Curnamona Province highlighting the general locality (outlined), the main geological and structural elements, and the palaeochannel-hosted uranium deposits.*

Groundwater use in the Curnamona Province is mainly restricted to isolated pastoral activities, particularly for stock watering (salinity permitting). To the north and north-east of the province, in the Frome Embayment of the Eromanga Basin, more abundant and lower salinity groundwater in the Great Artesian Basin (GAB) is accessible. Because of concerns about groundwater contamination caused by *in situ* leach (ISL) extraction of uranium at Honeymoon and Beverley, detailed environmental assessments have placed considerable effort in understanding the hydrogeological processes which occur in these palaeovalleys.

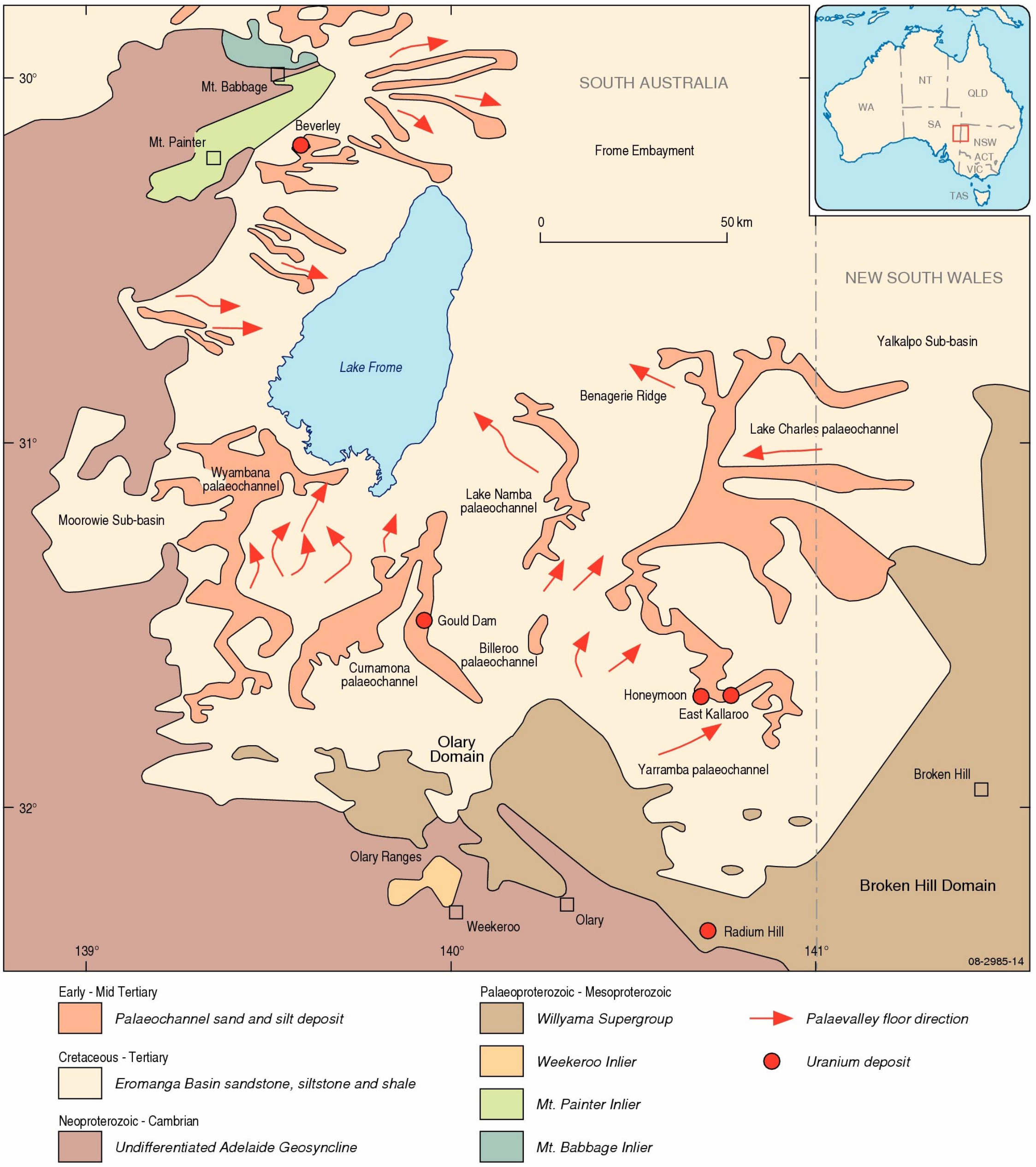


Figure 4.3: *Interpreted distribution of Cenozoic palaeochannels and groundwater flow vectors across the Curnamona Province. The location of significant palaeochannel-hosted uranium deposits is also shown.*

4.1.1. Palaeovalleys in the Honeymoon Region

A series of palaeovalleys extends northwards from the Olary Ranges towards the Callabonna Sub-basin of the Cenozoic Lake Eyre Basin. To the west of the Benagerie Ridge these include the Curnamona, Billeroo and Lake Namba Palaeovalleys, with the Yarramba, Beefsteak and Lake Charles Palaeovalleys occurring east of the Benagerie Ridge. Incision of the palaeovalleys into the bedrock terrane was initiated in the Late Palaeocene to Eocene. The palaeovalleys are sinuous and of variable width, for example, 6 kilometre maximum width for the Yarramba Palaeovalley and about 10 kilometre maximum width for the Billeroo Palaeovalley. They typically have broad, flat valley floors and variably shaped valley sides. Channel sinuosity and shape are largely controlled by the lithological composition and structure of the underlying basement rocks. The palaeovalleys of the Honeymoon region have no surface expression.

The palaeovalley infill sequence consists of basal Eyre Formation Eocene fluvial sands, which are contiguous with blanketing Eyre Formation sediments to the north. The basal sands are overlain by Miocene lacustrine (clay-rich) Namba Formation which forms the upper palaeovalley fill and extends laterally beyond the palaeovalley margins. The Namba Formation is itself overlain by undifferentiated Quaternary clay and sandy clay fluvial and aeolian sediments. The Yarramba and Billeroo Palaeovalleys host the Honeymoon, East Kalkaroo and Gould's Dam uranium prospects (Figure 4.3), and their infill sequences are relatively well-studied (Southern Cross Resources, 2000).

The Yarramba palaeovalley extends for more than 100 kilometres at an average depth of 70 metres below the surface and contains a valley fill sequence about 55 metres thick at Honeymoon (Figure 4.4). The Eyre Formation fluvial sands show rapid facies variation and are informally divided into four main units (basal, middle, upper and top) which each represent upward fining, commonly cross-bedded sequences typical of a braided-river environment. Fine- to coarse-grained angular sands are poorly sorted, quartz-rich and interbedded with kaolinitic clays. The Eyre Formation sediments are mostly oxidised with orange to yellow-brown iron oxide/hydroxide staining except in units with low permeability where reducing conditions are demonstrated by preservation of pyrite and organic matter. The uranium enrichment occurs at palaeochannel boundaries, along clay horizons and at oxidation-reduction interfaces, especially at the base of the sequence. The thick clay-rich Namba Formation has been deposited as floodplain overbank deposits and in valley lakes and swamps. The Namba Formation clays seal the Eyre Formation sands at the top and along the rising valley sides thereby forming an aquiclude which constrains groundwater migration within the lower valley sands.

The Billeroo Palaeovalley is similar to the Yarramba and extends northwards for at least 80 kilometres, where it joins the Curnamona Palaeochannel. It is up to 10 kilometres wide and occurs at an average depth of 90 metres, with about 50 metres of valley fill sediments. Valley sides dip more gently and are less variable than the Yarramba Palaeovalley. In-filling Eyre Formation sediments are divided into three fining-upward members; lower, middle and upper. The **lower member** has fine- to coarse-grained, angular, poorly sorted, quartz-rich sand and gravel with minor pyrite and organic matter. It is interbedded with grey, lignite- and mica-bearing silts and clays. The **middle member** consists of fine- to medium-grained sand, with micaceous and kaolinitic silt and clay. The **upper member** has a sequence of medium- to coarse-grained, well-sorted quartzose sand grading to fine sand and silt, with thin silcrete beds near the upper boundary. Brown, orange and pale yellow iron oxide/hydroxide stains on quartz grains indicates oxidation in the absence of pyrite and humic matter. The Namba Formation and undifferentiated Quaternary sediments, similar in thickness and composition to the Yarramba palaeovalley, overlie the Eyre Formation in the Billeroo Palaeovalley.

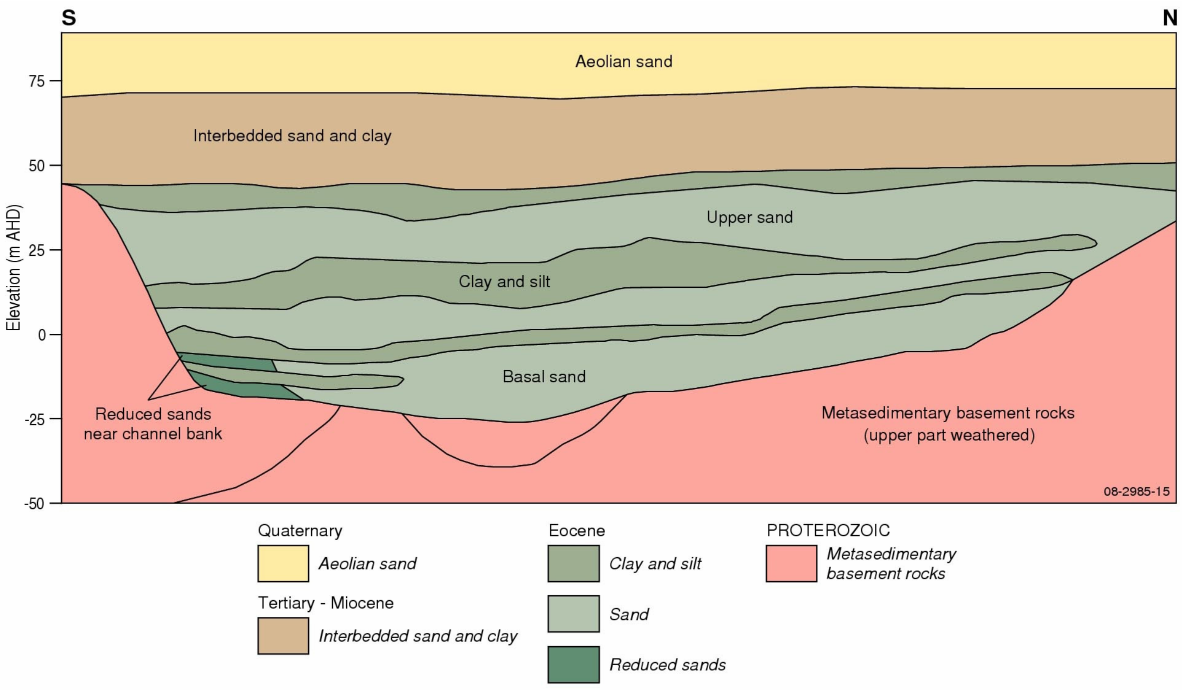


Figure 4.4: *Idealised north-south cross-section of the Yarramba Palaeovalley in the vicinity of the Honeymoon uranium deposit, showing the typical Cenozoic infill sequence of alternating sand- and clay-rich layers. The palaeovalley is incised into metasedimentary Proterozoic bedrock of the Curnamona Province (m AHD = metres above Australian Height Datum). Figure is modified from Southern Cross Resources (2000).*

4.1.2. Palaeovalley Groundwater in the Honeymoon Region

In the Honeymoon–East Kalkaroo area the palaeovalley system trends north-east, but elsewhere is generally oriented to the north (Southern Cross Resources, 2000). The palaeochannel sands form a multilayered aquifer, contained by overlying clays, which is recharged by a combination of rainfall infiltration in the Olary Ranges, lateral inflow from fractured and weathered basement rocks and throughflow from tributary palaeochannels. The regional groundwater flow direction is towards the north, in the direction of extensive Eyre Formation sediments in the Callabonna Sub-basin (1:1,000 gradient from Honeymoon to Lake Frome). Locally however, flow direction is determined by the geometric arrangement of the channel sand facies. In the Yarramba Palaeovalley Eyre Formation fluvial sands form a single semi-confined aquifer at the regional scale but they are subdivided locally at Honeymoon into three sand aquifers and three confining clay-rich layers. Additionally, a sand aquifer and confining clay-rich unit occur in the basal Namba Formation. Within the sandy palaeochannel units significant compositional variations occur due to depositional and erosional channel processes. These can occur over relatively short distances, resulting in significant differences in the thickness and hydraulic properties of aquifers and confining layers. In some places direct connection between aquifer units occurs. At Honeymoon, the basal and middle sands of the Eyre Formation are mostly separated by the widespread Middle Clay aquitard (3 metres average thickness), which restricts interflow of groundwater between the aquifer layers. Uranium mineralisation variably occurs in each of the Eyre Formation sand aquifers but the economic deposit is confined to single layers, or groups of thin sand layers separated by thin clay interbeds.

A program of hydraulic testing and monitoring of the three Eyre Formation aquifers at Honeymoon was part of the environmental impact assessment and *in situ* leach (ISL) trial procedure (Southern

Cross Resources, 2000). Test-pumping wells drilled at Honeymoon between 1980 and 1983 mainly targeted the Basal Sand aquifer, although some boreholes were also drilled in the Middle and Upper Sands for observation and water supply purposes (Table 4.1).

Table 4.1: Average values of Eyre Formation aquifer parameters determined from detailed pump testing at the Honeymoon uranium deposit (after Southern Cross Resources, 2000).

TRANSMISSIVITY (m^2/d)	HYDRAULIC CONDUCTIVITY (m/d)	STORAGE COEFFICIENT	LEAKAGE FACTOR (m)	HYDRAULIC RESISTANCE (D)
63	5	6.2×10^{-5}	110	200

Short-term constant discharge tests (varying from 3.25–8.0 litres-per-second) were conducted at Honeymoon in 1999 on selected regional monitoring wells to obtain transmissivity data and assess leakage between aquifers. These results determined that the Basal Sand and Middle Sand units are highly transmissive except at the western edge of the Yarramba Palaeovalley, probably due to compositional variations which control local aquifer thickness and permeability. Transmissivity was shown to be uniformly low in the Upper Sand unit. Drawdown responses indicated that the Middle Sand and confining layers do not permit hydraulic connection between the Upper Sands and Lower Sands. Relative groundwater levels in the main and tributary palaeovalleys imply that the aquifers are either at or near hydraulic equilibrium, and density-corrected data indicates only a small upward vertical hydraulic gradient. Potentiometric maps of the three aquifers show that the direction of groundwater flow is from north-east to south-west, with hydraulic gradients of ~1.5×10^{-4}. Calculated flow rates range from 10–16 metres-per-year for the Basal Sand and Middle Sand aquifers, and are <1 metre-per-year for the Upper Sand. The interpretation of stratigraphic cross-sections indicated throughflow rates of about 90 megalitres-per-year (ML-per-year), with minimal groundwater loss or addition along the flow path of the confined palaeochannel aquifer except from tributary channels. Laboratory-based hydraulic conductivity tests of the basal and middle aquitard layers indicated vertical hydraulic conductivity is very low (10^{-4}–10^{-6} metres-per-day), and an order of magnitude less for the Top Clay. Where present, the aquitard units significantly restrict movement of groundwater between aquifers.

The water quality within the palaeochannel aquifers at Honeymoon is generally poor (Southern Cross Resources, 2000). The concentration of total dissolved solids (TDS) in groundwater from the Upper Sand aquifer is generally >9,000 milligrams-per-litre (mg/L) and can exceed 20,000 mg/L in the Basal Sand unit. Salinity levels vary between aquifers and generally increases with depth; only groundwater in the Upper Sand can be used for stock-watering and then only after dilution with lower salinity surface water (if available from dams). Groundwater at Honeymoon contains abundant chlorine (mean = 53,700 mg/L), sodium (mean = 33,850 mg/L), sulfate (mean = 15,400 mg/L), calcium (mean = 560 mg/L), magnesium (mean = 270 mg/L) and bicarbonate (mean = 160 mg/L). Additionally, the concentration of radionuclides, including uranium and radium, considerably exceeds drinking water guidelines, with uranium at 60-times and radium at 340-times the recommended levels.

The Great Artesian Basin (GAB) occurs about 70 kilometres north of Honeymoon at the southern margin of the Frome Embayment. The main aquifer in the GAB, the Cadna-owie Formation, is here separated from the Eyre Formation by a significant thickness of clay-rich sedimentary rocks, part of the Marree Sub-group and equivalent to the Bulldog Shale aquitard. Confinement of the Eyre Formation aquifers, combined with the relatively higher potentiometric head in the Cadna-owie Formation, prevents downward leakage of Eyre Formation groundwater to the GAB.

The regional stratigraphic and hydrologic setting of the Eyre Formation aquifer in the Billeroo Palaeovalley is similar to the Yarramba palaeovalley, although the detailed stratigraphic architecture is less constrained. There are three semi-confined sand aquifers separated by significant clayey aquitards. The hydraulic transmission parameters of these sediments, as determined from well-pumping tests, are not yet publicly available for the Billeroo palaeochannel.

4.1.3. Palaeovalleys in the Beverley Region

To the west of Lake Frome, palaeovalleys extend from the Flinders Ranges to the Cenozoic Callabonna Sub-basin and overlie Mesozoic sedimentary rocks of the Eromanga Basin. There are distinct stratigraphic differences in the nature of the Beverley Palaeovalley compared to those at Honeymoon, although palaeovalleys in the Beverley region also host economic uranium mineralisation. The Eyre Formation is absent from the Beverley region but forms blanket fluvial sand deposits further to the east; these consist of uncemented quartz sands with minor clay and lignite lenses, generally capped by silcrete. The Central and South Palaeovalleys at Beverley host the main uranium orebody and are formed within and filled by Miocene Namba Formation sediments.

The unconsolidated Namba Formation is subdivided regionally into two horizons (Callen and Tedford, 1976), the black, clay-rich Lower Namba Alpha Mudstone and the variably sand-, silt- and clay-bearing Upper Namba unit. The Lower Namba Alpha Mudstone is generally hard and poorly laminated, and consists of dark-brown to black clay with minor oxidised yellow-brown bands and black organic matter (plant fragments and carbonised wood). It is >50 metres thick in the vicinity of Beverley and the upper boundary is a low-relief, undulating palaeo-surface incised with easterly to south-easterly trending palaeovalleys. The Upper Namba Formation consists of the Beverley Sands, forming the palaeovalley fill sequence, and the overlying Beverley Clay. The Beverley Sand unit consists of mature and well-sorted, fine- to medium-grained quartz-rich silty sands, with minor clay and organic-rich intraclasts. The sandy layers lack gravels and are interbedded with minor sand-rich clays, silt and clay. The uniform sand-rich layers within the Beverley Sands were deposited in channel, bar and floodplain fluvial environments with intertwined cut-and-fill braided channel sequences. The silt content of the lower Beverley Sand unit, which occurs exclusively within the palaeovalleys, increases eastwards. The upper part of the Beverley Sands form an upward-fining sheet dominated by fine sand, silt and clay with fewer inter-channel features. These are interpreted to have formed in progressively waning-energy braided stream environments. The uppermost sub-unit of the Namba Formation, the Beverley Clay, is widespread and consists of hard, grey and brown clay with minor silt and sandy-clay interbeds. It caps the Beverley Sands, where present, and extends beyond the palaeovalleys to directly overlie the Alpha Mudstone.

The Willawortina Formation, comprising up to 150 metres of Miocene to Early Pleistocene alluvial fan deposits, overlies the Namba Formation and thins towards the east, away from the Flinders Ranges. Colluvial, fluvial and aeolian sediments of Quaternary age overly the Willawortina Formation. Uranium mineralisation is concentrated in the Beverley Sands, effectively an aquifer confined between the Alpha Mudstone and the Beverley Clay/Willawortina Formation.

4.1.4. Palaeovalley Groundwater in the Beverley Region

In the Beverley area of the western Frome Embayment, groundwater occurs in multiple aquifer systems, with aquitards occurring both between and within each aquifer (Heathgate Resources, 1998). Recognised aquifer systems (from oldest to youngest) are the:

- Fractured-rock aquifers in the geological basement;
- Cadna-owie Formation aquifer of the Great Artesian Basin;

- Eyre Formation aquifer;
- Namba Formation Beverley Sands aquifer;
- Willawortina Formation aquifer; and
- Surficial Quaternary stream aquifers.

The fractured rock aquifers are recharged directly by rainfall in the Flinders Ranges. Groundwater in the fractured rock system has total dissolved solids (TDS) of 1,000–10,000 mg/L, and discharge occurs into ephemeral creeks, range-front springs and probably into the sedimentary rock aquifers further east (where connected). The Beverley region occurs at the margins of the Cadna-owie Formation (part of the GAB) and discharge occurs via mound springs (on Lake Frome and to the north) and slow leakage through aquitards (whereby it can enter overlying aquifers). Boreholes into the main GAB aquifer in this region have variable flow rates and salinity levels, for example, Camp Bore near Beverley flows at 5 L/s and has a salinity of 2,200 mg/L. The Eyre Formation does not occur at Beverley but, further south, contains poor quality groundwater with TDS ranging from 3,000–10,000 mg/L.

The Lower Namba Formation Alpha Mudstone is a widespread aquitard at Beverley, where it varies from 50–100 metres in thickness. The Beverley Sand aquifer is restricted to deeply incised and steep-sided channels in the palaeovalleys and grades laterally at its margins to mud-rich overbank deposits. Both the Alpha Mudstone and the fine-grained overbank facies are effective lateral barriers which restrict groundwater flow within the more permeable palaeochannel facies. For example, the Beverley Sand aquifer is highly permeable, especially along-channel (down-stream) due to its origin in braided stream environments. Pumping tests have indicated minor intra-formational hydraulic leakage within the Beverley Sand aquifer due to channel-within-channel lenses. These pump-tests also showed significant aquifer confinement by the Alpha Mudstone and the Namba Clay, with no indication of leakage (even near old exploration boreholes). Groundwater levels in the Beverley Sand (Namba Formation) aquifer are about 60 metres below ground-level. The drawdown response to pumping is rapid and recovery is slow, indicative of the hydraulic isolation of the aquifer. Groundwater salinity levels are 3,000–15,000 mg/L with no indication of salinity stratification within the aquifer at Beverley, although salinity probably increases down-channel towards the evaporative concentration zone at Lake Frome. Groundwater in the Beverley Sand aquifer at the Beverley mine is generally unsuitable for stock-watering due to high salinity. The gradient in the aquifer suggests stagnation of groundwater flow. The concentration of uranium in groundwater within the Beverley Sand aquifer is mostly <1 milligram-per-litre (mg/L) and rarely exceeds 10 mg/L.

The Willawortina Formation contains a number of thin aquifers which are of variable permeability and low interconnectivity, typical of alluvial fan sediments. The unit is water-saturated below about 60 metres although groundwater yields are mostly low. Pastoral bores which tap the Willawortina Formation indicate that the potentiometric surface is about 5 metres AHD near Lake Frome and up to 20 metres AHD near Beverley, indicating a subtle west to east groundwater flow gradient towards the lake.

4.2. LAKE EYRE BASIN

The Cenozoic Lake Eyre Basin (Callen et al., 1986) contains abundant and widespread fluvial, lacustrine and aeolian sediments of Eocene, Oligo-Miocene, Pliocene and Quaternary age, including palaeovalley deposits. The basin is the site of prolonged mid-continental subsidence extending to Mesozoic and earlier-formed basins. The Cenozoic sedimentary record of the Lake Eyre Basin contains extensive fluvial deposits of the Eocene Eyre Formation and lacustrine deposits of the

Oligo-Miocene Etadunna Formation. These sediments form sheet or blanket cover sequences and palaeovalley infill. The Lake Eyre Basin palaeovalleys (Figure 4.5), which merge with the Eyre and Etadunna Formations, undoubtedly extend:

- East from the Stuart Range and the Proterozoic Peake and Denison Range inliers;
- North from the Flinders Ranges;
- West and south-west from the Eastern Highlands; and
- South from the MacDonnell Ranges where the present-day drainages of the Finke, Hugh, Todd, Hales, Hay and Plenty Rivers merge with the Simpson Desert.

The Lake Eyre Basin substantially overlies the Mesozoic Eromanga Basin, with its reliable and abundant groundwater resources, i.e., part of the Great Artesian Basin (GAB). Hence, the Lake Eyre Basin extends beyond the geographic limits of the Palaeovalley Groundwater Project (as discussed in Chapter 1). However, the well-studied Nelly and Powell Creek Palaeovalleys south-west of Lake Eyre, and the Stuart Creek and Mirackina palaeovalleys near the margins of the Lake Eyre Basin, occur at or beyond the GAB and so are discussed briefly below.

The palaeovalleys of the Lake Eyre Basin contain basal Eyre Formation (or equivalent) fluvial deposits dominantly of Middle Eocene age (Drexel and Preiss, 1995; Alley et al., 1999). Typical sediment sequences consist of basal conglomerate with highly polished, resistant pebble clasts overlain by cross-bedded mature pyritic and carbonaceous sands up to 5–10 metres thick. Lignite and clay units, containing plant fossils, also occur, probably representing back-swamp and valley-lake settings in the wider braided stream palaeo-environment. The upper part of the lower fluvial unit is commonly silicified, and silcrete deposits of the Stuart Creek, Poole Creek and Nelly Creek Palaeovalleys contain relatively abundant and well-preserved plant macrofossils (which have greatly elucidated the Eocene flora of central Australia). The Oligo-Miocene dolomitic lacustrine sequence of the Etadunna Formation is widespread in the Lake Eyre region; however sediments of that age are less common in the palaeovalleys. The Poole Creek palaeovalley (Alley et al., 1999) contains silicified basal Oligo-Miocene sand with a basal silcrete pebble lag overlain by cross-bedded sands with dolomite lenses which contain plant fossils; the sands interfinger laterally and vertically with more extensive dolomite (equivalent to Etadunna Formation dolomite). The silicified Willalinchina Sandstone of the Stuart Creek palaeovalley, which is rich in fossilised plant material, is now regarded as probably equivalent to the basal Oligo-Miocene sands of the Poole Creek Palaeovalley (Alley et al., 1999), though they were earlier regarded as Eyre Formation equivalents (Drexel and Preiss, 1995). The Mirackina Palaeovalley may also contain silicified Oligo-Miocene sand and gravel deposits (Drexel and Preiss, 1995).

No detailed studies of palaeovalley groundwater systems in the south-west Lake Eyre Basin were located during this investigation.

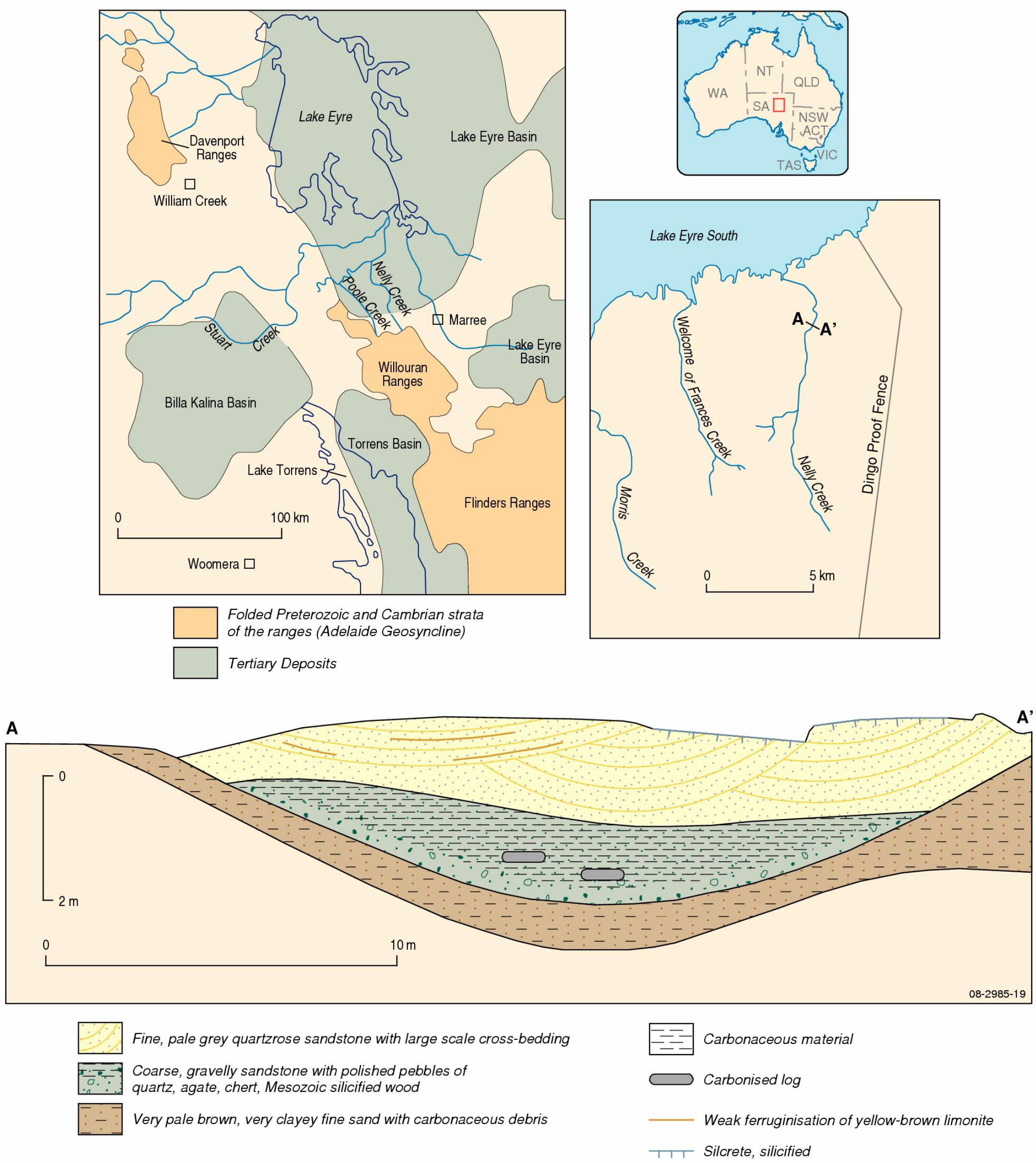


Figure 4.5: *Distribution of palaeovalley systems and Cenozoic sediment deposits, including palaeovalley infill, in the Lake Eyre Basin. The cross-section shows idealised Cenozoic infill profile developed within an incised palaeovalley in the Lake Eyre region.*

4.3. CENTRAL AUSTRALIA

The central Australian region here refers to drainage systems both north and south of the upland Central Ranges in the vicinity of Alice Springs. The Central Ranges broadly consist of two distinct geological provinces, based on diverse structural characteristics (Mabbut, 1967). The northern Central Ranges are rugged uplands of well-exposed crystalline rocks, mostly gneiss and schist, which represent the southern fringe of the Warumpi Province of the Proterozoic Arunta Block. The region includes the northern MacDonnell Range and the Harts Range. To the south the Central Ranges consist of parallel strike ridges of folded sedimentary rocks within the 170,000 kilometre^2 Proterozoic to Palaeozoic Amadeus Basin. Prominent ridges are dominated by sandstone and quartzite in the west, and also include limestone in the east. A broader belt of ridges to the south and east forms the Krichauff, James and East MacDonnell Ranges and a narrower, more strongly folded belt forms the West MacDonnell Ranges in the north-west. The two belts enclose the synclinal Missionary Plain. Also included in the study region, are parts of the southern Georgina Basin and the Ngalia Basin, an east-trending intracratonic basin some 80 kilometres north of the Amadeus Basin. Both the southern Georgina Basin and Ngalia Basin mainly contain Neoproterozoic to Palaeozoic sedimentary rocks.

The geological nomenclature for Cenozoic depositional systems in central Australia is dominated by discrete basins and has previously made minimal reference to palaeovalleys (Table 4.2 and Figure 4.6). However, recent hydrogeological mapping of the Northern Territory has partly elucidated the palaeodrainage pattern and suggested limited interconnection of Cenozoic basins and palaeovalleys (Tickell, 2008). The modern drainage pattern in central Australia tends to be transverse to the trend of the main mountain ranges; for example, the Finke River and its many tributaries begin in the northernmost part of the MacDonnell Ranges and maintain predominantly southerly courses via spectacular water gaps through strike ridges and meandering gorges of the James Range plateaux. Mabbut (1976) interpreted this discordant pattern as inheritance from pre-Cenozoic drainage patterns. English (2002) related the prevalent southerly drainage pattern to pervasive joint systems that developed as part of the long-lasting (ca. 100 million years) Palaeozoic Alice Springs Orogeny when the region was subjected to prolonged north-directed compression. More recent down-warping (possibly early Cenozoic?) along ancient east-striking faults in the northern MacDonnell Ranges resulted in beheading and capture of some south-flowing drainage systems which then feed into the various newly-formed piedmont Cenozoic basins, such as the Hale and Ti-Tree Basins. These basins contain fluvial and lacustrine sediments and, for the most part, can be regarded as Cenozoic palaeovalley or palaeovalley-related systems. Depending on the age of basinal formation by down-warping they may contain basal Eocene fluvial or lacustrine sediments – a possibility generally unresolved in central Australia due to lack of drilling through the entire Cenozoic sequence to the underlying basement. If these basins contain basal Eocene lacustrine sequences it seems highly probable that the lakes would have overflowed and been interconnected by river systems which should now be preserved as palaeovalleys (as suggested by the recent hydrogeological mapping of Tickell, 2008). The nature of basal sediments in these palaeodrainage systems would depend on the provenance, i.e., the type of source material available, such that fine-grained silt and clay deposits may be more common than sand and gravel in relatively low-energy fluvial and lacustrine environments.

Table 4.2: Cenozoic basins surrounding the central Australian uplands.

LOCATION	CENOZOIC BASINS	COMMENTS
Northern Territory	Mount Wedge, Lake Lewis, Burt, Witchetty, Yaloogarie, Willowra, Warrabri, Ti-Tree, Waite, Bundey, Hale, Arema, Farm, Santa Teresa	Refer to Senior et al. (1994) and Langford et al. (1995) for further details.
South-western Queensland	Marion, Old Cork, Springvale	These overlie the Mesozoic Great Artesian Basin but are separate from the Lake Eyre Basin.
Northern South Australia	Hamilton, Billa Kalina, Torrens	

The central Australian basins occur either near bedrock ranges that provide relatively high amounts of runoff, or they underlie major ephemeral rivers which promotes direct streambed recharge during peak flood periods, e.g., from the Georgina and Diamantina Rivers that rise in monsoon-influenced parts of north Queensland. Accordingly, recharge to shallow aquifers may be significant and palaeovalleys here are highly prospective for shallow groundwater resources. The piedmont Cenozoic basins of central Australia may host palaeovalley aquifers that store substantial potable groundwater resources (English, 2002).

Figure 4.6: *Distribution of Cenozoic sedimentary basins and the modern ephemeral drainage pattern in central Australia. Figure is modified from Senior et al. (1995) and English (2002).*

4.3.1. Central Australian Basins

Senior et al. (1994, 1995) investigated palaeovalley and basin fill deposits in several terrestrial Cenozoic basins in central Australia. These extend across an area of several hundred kilometres both north and south of Alice Springs, and include the Lake Eyre Basin and several smaller satellite basins in adjacent parts of the Northern Territory, South Australia and Queensland (Figure 4.6). Palaeovalley infill sequences are >200 metres thick in some basins and the sediments are deeply weathered and rarely exposed, except near the bedrock ranges where more recent alluvium has been deposited near debouchment points. These palaeovalley sequences overlie weathered and ferruginised bedrock and generally comprise basal Eocene sediments overlain by Oligo-Miocene sediments (Figure 4.7), although accurate age dating is poorly constrained due to deep weathering profiles and highly degraded pollen.

The basal Hale Formation of probable Eocene age comprises up to 55 metres of kaolinitic, argillaceous, poorly sorted sand with granule- and pebble-sized gravel beds, especially at the palaeovalley margins (Figure 4.7). The Hale Formation is overlain by carbonaceous shale or lignite lenses <4 metres thick, mud- and silt-rich layers, and an upper sandy unit known as the Tug Sandstone (silicified). The Hale Formation was initially deposited under high-energy fluvial conditions which were gradually replaced by relatively quiet swamp-like environments. The Ulgnamba Lignite (Truswell and Marchant, 1986) and the upper Tug Sandstone were formed in a low-energy fluvio-lacustrine setting. The overlying Miocene sediments are fine-grained clastics consisting of interbedded, silicified calcarenite, sand, silt and minor gravel with chalcedony and carbonate in the uppermost sequence. These Cenozoic sediments were deposited in fluvial, deltaic and progressively drying lacustrine conditions and have been subjected to significant post-depositional weathering and ferruginisation (Senior et al., 1994; 1995).

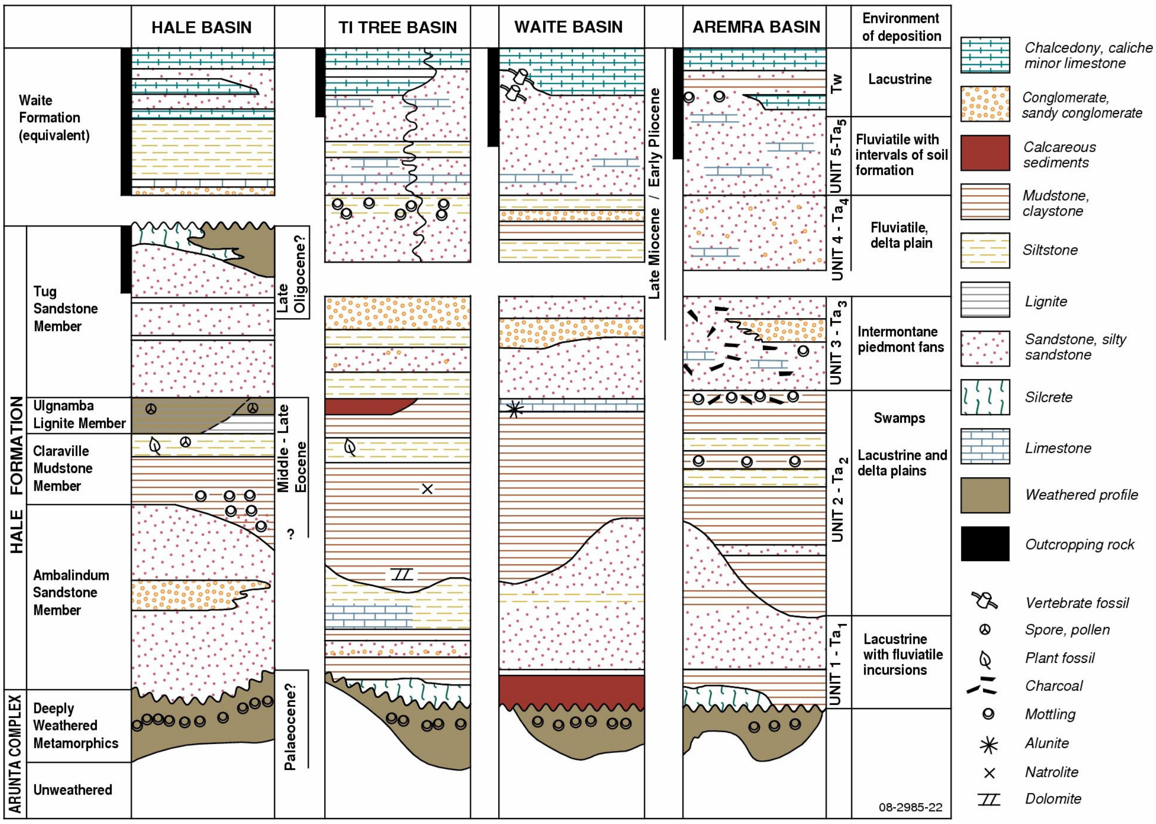


Figure 4.7: *Idealised stratigraphic correlation chart for selected Cenozoic basins which overlie the eastern Arunta Block in central Australia. Figure is modified from Senior et al., 1995 (Figure 9).*

North of the Central Ranges the palaeovalley drainage pattern and stratigraphic record are less well-known than the south-draining palaeovalleys around Alice Springs, with the exception of the Willowra and Ti-Tree Basins. These basins have been investigated due to their potential for groundwater-supported horticulture (further discussed below). A Cenozoic basin-and-range province is interpreted north of the main bedrock ranges, where respective basins – including the Burt, Lake Lewis, Mt Wedge and Witchetty Basins (Figure 4.6) – are bordered by the West MacDonnell Ranges (to the south) and the Stuart Bluff Range (to the north) (English, 2002). An Eocene lacustrine clay unit known as the Mt Wedge Clay overlies crystalline bedrock and is up to

100 metres thick (Lau et al., 1997). This basal clay infills depressions that may have been formed by flexural down-warping of basement blocks along ancient faults; the unit is tentatively correlated with the Eyre Formation in South Australia (English, 2002). The palaeoenvironment of the Eyre Formation is interpreted as warm, wet, and probably monsoonal, with rainforest vegetation along water courses and more open woodland between creeks and swamps (Krieg, 1990). In the Lake Lewis, Burt and Mt Wedge piedmont basins, the basal lacustrine clays are overlain by up to 100 metres of Miocene to Pleistocene alluvial fan deposits and more distal fluvial palaeovalley sediments. These are valuable freshwater aquifers in the modern environment. Subordinate Quaternary aeolian sand deposits overlie much of the region (English, 2002). In the Witchetty Basin, Kemp (1976) identified pollen from aquatic and marsh plants and dinoflagellate cysts indicative of Eocene lacustrine conditions. Based on palynology, the Witchetty Basin deposits correlate with Eocene deposits of the Hale Basin, 200 kilometres to the east.

4.3.1.1. Central Australian Basin Chronology and Evolution

In common with other early and middle Cenozoic depositional systems the central Australian Cenozoic basins are difficult to accurately date; palynology currently provides the most accessible and cost-effective method although it is hampered by poor preservation of pollen and spores. Macphail (1996, 1997) has summarised the chronological evolution of the central Australian basins and reconstructed the palaeoenvironment and palaeoclimate based on vegetation associations inferred from pollen assemblages. These initial interpretations have been further enhanced by subsequent studies (Macphail, 2007). Constraints on palynology in the central Australian region are discussed by Macphail (1996, 1997) and include:

- A general paucity in the Cenozoic sequence of carbonaceous horizons and lignite. These sediments are best for preserving pollen and spores, particularly in Neogene deposits. The quantity, diversity and preservation of pollen and spores varies markedly between and within basins and over short depth intervals, e.g., within individual drill cores.
- A strong alteration and oxidation overprint due to Neogene and Quaternary weathering and groundwater flow. Except for the Hale Basin, Cenozoic sediments in central Australian basins above 40–60 metres do not contain pollen or spores.
- The absence of index and age-diagnostic taxa. Most taxa are long-ranging and at best support a non-specific Cenozoic age. However, changes in relative abundance of common dryland taxa may allow for correlation between sequences and provide some indication of age.
- Although herbaceous wetland taxa are relatively common, they are unreliable age indicators as their distribution is controlled by the level of the watertable.
- There are various problems caused by drilling, including vertical mixing and contamination between horizons and the introduction of anomalous pollen or spores in drilling fluids.
- There is wide geographic and environmental separation between the central Australian basins and other Cenozoic sediment sequences in Australia which have relatively good age control and well constrained pollen sequences, e.g., the Gippsland, Murray and Bonaparte Basins. Few diagnostic indicators from those basins are present in central Australia, and the local arrival or extinction times of particular taxa may also be different.

Macphail (1996) analysed 41 samples of thin lignite and other carbonaceous layers from cores described by Senior et al. (1994). This work was further augmented by an additional 35 samples from organic-rich zones in drill cores from various Cenozoic basins (Macphail, 1997), plus another seven samples collected during the Western Water Supply study to the west of Alice Springs (Section 4.3.3). Macphail (1996) identified three broad phases of Cenozoic deposition in the central

Australian basins but subsequently suggested that accumulation of organic material may have been quasi-continuous from the Late Cretaceous (Maastrichtian) to the Miocene, with irregular preservation of organic-rich sediments within particular basins (Macphail 1997). The three main depositional phases recognised by Macphail (1996) were:

- **Early Eocene:** recognised from the Santa Teresa Basin and the Ti-Tree Basin. Widespread indications of Early Eocene pollen reworked into Middle and Late Eocene sediments.
- **Middle to Late Eocene:** deposits include the Ulgnamba Lignite in the Hale Basin, which transgresses from Middle to Middle-Late Eocene. Time equivalents were recognised in the Burt, Ti-Tree (uncertain) and Santa Teresa Basins, and correlated with assemblages described by Kemp (1976) from the Napperby-1 drill core in the Witchetty Basin.
- **Oligo–Miocene:** recognised at depths of about 130 metres below a 60 metre thick weathering profile in thick calcareous claystone and siltstone deposits of the Burt Basin. These overlie Middle to Late Eocene mudstone which contains pyritic and carbonaceous material.

Additionally, there are equivocal indications of deposition during the Late Miocene and Pliocene from the upper part of the Hale Basin. Core samples analysed from the Ngalia Basin and the Waite Basin (Alcoota fossil site) did not contain pollen or spores.

Macphail (1997) described organic-rich deposits overlying basement near Uluru as belonging to the Ayers Rock Basin. Although originally interpreted as Palaeocene (by Truswell, 1987), Macphail (1997) confirmed the work of Twidale and Harris (1991) and assigned these basal sediments to the Late Cretaceous (Maastrichtian). These sediments occur in the lowest portions of the Dune Plains Palaeovalley, a tributary of the Karinga Palaeovalley in the Amadeus Basin (Jacobson et al., 1988, 1989; English, 1998a). Additionally, Macphail (1997) identified basal organic sediments of Maastrichtian age in the Bundey Basin, possibly overlain by Early Eocene deposits. Macphail (1997) also confirmed that deposition occurred in the Early Eocene within the Santa Teresa Basin, and that various sediments of Early Eocene, Middle to Late Eocene and Oligo–Miocene age were deposited in the Ti-Tree Basin. Most analysed samples from the Western Water Study did not contain pollen although tributary palaeovalley sediments drilled 12 kilometres west of Kintore yielded Oligo–Miocene carbonaceous stringers in a 30 metre-thick sequence of upper calcrete overlying interbedded sand and clay.

The organic-bearing facies which occur in the central Australian basins were mainly deposited in low-energy fluvio-lacustrine environments, but the presence of minor coarse-grained sediments indicates intermittent higher energy fluvial and probable erosive conditions. Fresh- to brackish-water predominated (abundant *Botryococcus*) in steams or lakes with sluggish flow; these were lined by wetlands and gallery evergreen forests (non-seasonal megatherm–mesotherm conditions). The preservation of organic matter was most effective in the Early and Middle to Late Eocene when the central Australian climate was drier than coeval coastal environments, but substantially warmer and wetter than at present. However, conditions are interpreted to have been cooler than the Late Palaeocene thermal maximum. Macphail (1997) suggested that the Middle Eocene migration of *Nothofagus* into central Australia was due to the onset of seasonal and cooler climate conditions across the continent.

Late Cretaceous deposits are restricted to the Ayers Rock and Bundey Basins, which preserve Maastrichtian organic matter overlying Proterozoic to Cambrian basement rocks at the margins of the Arunta Block. There is no compelling evidence for Palaeocene deposits and Macphail (1997) suggested that the tectonic development of Cenozoic basins across the Arunta Block probably occurred during the Palaeocene or earliest Eocene. In addition to Late Cretaceous deposition in basins marginal to the Arunta Block, Cenozoic basins consistently contain sediments of Early Eocene, Middle to Late Eocene and Oligo-Miocene age. The youngest organic facies reported by Macphail (1997) are Late Pliocene lignite beds at Tempe Downs, which are surprisingly well preserved considering the extensive Neogene weathering profile which is typical of the region. The lack of Oligo–Miocene and later organic matter is due to fragmentation of drainage systems which led to the formation of isolated ephemeral lakes.

English (2002) provided a detailed description of the Cenozoic evolution and sedimentation history of the contiguous basin-and-range province of the Burt–Lake Lewis–Mount Wedge region of central Australia. In this area a sequence of up to 100 metres of Palaeogene sediments overlies the crystalline basement. These are pyrite-bearing, grey-green lacustrine clays of probable Eocene age, known as the Mount Wedge Clay, which infill east-striking depositional troughs north of the West MacDonnell Ranges. Contemporaneous sedimentation occurred north of the Stuart Bluff Range, in Witchetty Basin, in a separate depocentre which was not connected with the evolving Cenozoic basins to the south. A second major phase of deposition in the Burt–Lake Lewis–Mount Wedge Basins occurred in the Neogene, with the depocentres migrating northwards and becoming more isolated from each other due to intervening basement highs influencing drainage patterns and fluvial–lacustrine sedimentation. Up to 100 metres of sediments deposited in alluvial fan, palaeochannel and overbank conditions accumulated in the piedmont zone immediately north of the MacDonnell Ranges during the Miocene and Pleistocene. These sediments were derived from very large, mountainous headwater catchments, with sedimentation enhanced by uplift of the ranges and/or subsidence of the basins to the north (English, 2002). The reddish Neogene sediments are highly oxidised and heterogeneous and sharply overlie the basal Palaeogene clay. Deposition of the alluvial fan facies was probably coeval (temporally) with down-gradient deposition of lacustrine clay deposits. For example, the Anmatyerre Clay at Lake Lewis, which is up to 80 metres thick and extends over 3000 kilometres^2, commonly infills depressions in the highly irregular basement. Witchetty Basin to the north also accumulated significant fluvial deposits during the Neogene; drainage systems eventually flowed through gaps in Stuart Bluff Range to feed Lake Lewis to the south (English, 2002). At least nine vertical metres of uniform Anmatyerre Clay was deposited in Lake Lewis over the last 780,000 years, since the Brunhes–Matuyama magnetic polarity reversal. Optically Luminescence (OSL) dating reveals that dunefields formed on the basin >95,000 years ago, and that gypsum-rich aeolian deposits accumulated between 80,000–17,000 ka (English, 2002, English et al., 2001; Chen et al., 1995). Wetter conditions ensued, characterised by floodplain deposition and episodic shallow inundation of the lake during the past 20,000 years (English et al., 2001).

4.3.2. Central Australian Groundwater Resources

Quinlan (1961) provided one of the first regional assessments of groundwater reserves and characteristics in central Australia. Groundwater recharge is irregular and depends largely on rainfall intensity. The most effective recharge occurs where runoff from adjacent ranges is channelled over permeable beds with watertable access, although minor direct recharge from local rain events may also occur. Runoff levels are relatively high from elevated Precambrian and Palaeozoic bedrock terranes which surround many basins. A moderate amount of runoff occurs in low relief landscapes which variably consist of soil, ferricrete and Mesozoic/Cenozoic rocks. In comparison, runoff is rare across Quaternary alluvial and playa sediments as most is lost to evapotranspiration. Groundwater storage volumes are much greater than the annual amount of runoff; discharge generally occurs in the eastern part of the central Australian region by outflow to the Lake Eyre Basin or the Great Artesian Basin, and in the west by evaporation from playas or transpiration by vegetation where the watertable is shallow. Groundwater occurs in three main types of aquifer:

- **Fractured and weathered metamorphic and igneous basement rock aquifers**, which provide variable (low to moderate) groundwater supplies which are generally sparsely available.
- **Lower Proterozoic to Palaeozoic sedimentary rock aquifers**, which can provide significant amounts of potable water, but commonly occur at considerable depth.
- **Cenozoic sediments**, including terrestrial basin deposits which have low storage coefficients (<0.05) but relatively large saturated volumes; aquifer characteristics are highly variable although most are interconnected and include calcrete deposits.

Groundwater salinity is a complex function of weathering, recharge, evaporation and throughflow. Potability is limited not only by total salinity but also by the abundance of toxic ions such as fluorine (upper limit of 1 milligram-per-litre (mg/L), magnesium (200 mg/L), sulfate (375 mg/L), chlorine (375 mg/L) and nitrate (44 mg/L). Where available, groundwater resources are generally adequate for pastoral use, as these are less affected by salinity and volume constraints. Many central Australian towns and aboriginal communities, including Kulgera, Yuendumu, Aileron, and Barrow Creek, have limited groundwater supplies because they occur on basement rocks. Papunya, Amoonguna and Warrabri are located on Cenozoic sediments which have adequate groundwater resources. The Alice Springs town water supply was initially derived from the shallow alluvial aquifer of the Town Basin. This was later supplemented from the nearby Cenozoic Inner Farm Basin, and then replaced by groundwater supplies from the sedimentary rock aquifer of the Palaeozoic Mereenie Sandstone in the Amadeus Basin. Quinlan (1961) identified 17 districts in central Australia where groundwater-supported horticulture could be developed with further investigation; these included 14 areas underlain by Cenozoic basins. Recommendation of these sites was based on:

- The known presence of low-salinity groundwater with low levels of sodium.
- The relatively shallow level of the watertable, generally >30 metres and many >15m.
- The potential to develop high-yielding groundwater bores.
- Significant levels of recharge from runoff.
- Groundwater storage volumes much greater than recharge.

The various central Australian Cenozoic basin and palaeovalley systems contain important groundwater resources targeted for investigation as part of the Palaeovalley Groundwater Project. For example, the Haast Bluff Aboriginal Land Trust is within the Mount Wedge Basin and part of the adjacent Lake Lewis Basin, and was partially investigated during the Western Water Supply project in the late 1990's. Likewise, the Willowra–Mt Barkly site occurs within the Willowra Basin (defined by Senior et al., 1995) and is adjacent to the significant fresh groundwater resources of the Ti- Tree Basin, which have supported horticultural developments during the last decade (McDonald, 1988; Harrington et al., 1999; 2002).

In the Lake Lewis Basin there are three main aquifers: 1. weathered, fractured bedrock aquifers; 2. Neogene alluvial and lacustrine sediment aquifers in the upper 60 metres of the basin; and 3. near-surface silicified calcrete aquifers (English, 2002). Poor water-holding capacity and transmissivity typifies the ~100 metre thick basal Palaeogene clay sequence, the lacustrine Mount Wedge Clay, and no bores are developed within this unit. Faults and basement structures substantially influence groundwater processes in the basin, including flow between the different aquifer types and discharge into Lake Lewis. Palaeochannel and palaeodeltaic sediments are the most important aquifers in terms of groundwater supplies and system throughflow (English, 2002). Hydraulic connectivity is relatively poor between bedrock aquifers in the MacDonnell Ranges and the Cenozoic alluvial aquifers in the adjacent basin. This is mainly due to obstruction o f groundwater flow by basement highs which underlie the piedmont zone, including beneath the debouchment outlets of the major creeks. The large headwater catchments, nonetheless, are important components of the ephemeral surface drainage systems and provide significant recharge volumes for alluvial aquifers – particularly palaeovalley aquifers – in the piedmont zone (English, 2002).

The depth to the water table in Lake Lewis Basin varies between the different aquifers. The watertable is generally >45 metres deep in bedrock aquifers, 15–45 metres deep under the alluvial plain, and <15 metres beneath the lacustrine plain surface, shallowing to about 1 metre deep at the playa (English, 2002). Potentiometric contours show a centripetal groundwater flow pattern from the basin perimeter to Lake Lewis, parallel to the surface drainage pattern. The hydraulic head across groundwater intake zones in the piedmont is approximately 580–590 metres AHD, which drives groundwater flow towards Lake Lewis (550 metres AHD), situated some 50 kilometres to the north. Groundwater discharge is concentrated along linear springs at the playa margins, particularly along a fault beneath the southern edge of the playa (English, 2002). The groundwater salinity gradient across the basin is well-defined from about 100 bores, ranging from fresh water (<500 mg/L total dissolved solids or TDS) at intake aquifers to playa brines of >200,000 mg/L TDS. The alluvial plain is underlain by aquifers with fresh to moderate salinity groundwater (<2,500 mg/L TDS), the lacustrine plain has brackish to saline groundwater (2,500–10,000 mg/L TDS) with a steep gradient thereafter over a horizontal distance of a few kilometres to the brine pool at Lake Lewis. The brine pool occurs across 650 kilometres^2 and includes the main playa and an aureole of small salt pans. Major ion trends along the hydrologic gradient are dominated by linear accumulations of sodium, potassium and sulfate (with respect to chloride); down-gradient deflections occur in the trends of bicarbonate and calcium versus chlorine because of lake-ward precipitation of calcite ($CaCO_3$) and gypsum ($SO_4 \cdot 2H_2O$). A significant amount of dissolved silica accumulates in aquifers due to weathering of granite and granitic alluvium within the catchment. Dissolved silica ($SiO_{2(aq)}$) concentrations of 100–150 mg/L in groundwater from Cenozoic aquifers decrease in the lower part of the hydrologic gradient to <10 mg/L in playa brines due to precipitation of opaline and chalcedonic silica ($SiO_2.H_2O$) in the karstic calcrete aureole surrounding Lake Lewis. This represents a response to evaporative concentration of silica in the near-surface environment close to the groundwater discharge zone. Silicified calcrete commonly forms a surficial (rain-fed) aquifer that can store a significant amount of relatively fresh groundwater compared to non-silicified calcrete (English, 2002). The level of low dissolved silica in the playa brine causes aluminosilicate minerals within the palaeolacustrine clay to become metastable, thereby promoting the *in situ* crystallisation of authigenic zeolite minerals, particularly Na-rich analcime (English, 2001).

4.3.3. Western Water Study Region Groundwater Resources

The Western Water Study of the mid- to late-1990's investigated the groundwater resources of 60,000 kilometres^2 of mostly aboriginal land in the western MacDonnell Ranges, extending to the Western Australian border (Wischusen, 1998; Jamieson, 1998, Hostetler et al., 1998). The study area included the aboriginal communities of Haast Bluff, Papunya, Yuendumu, Mount Liebig, Nyirripi, and Kintore as well as the pastoral stations of Mt Doreen, Newhaven, Gurner, Central Mt Wedge and Derwent. The project partners were the Northern Territory Department of Lands, Planning and Environment (NTDLPE), the Australian Geological Survey Organisation (AGSO), the Central Land Council (CLC) and the Aboriginal and Torres Strait Islander Commission (ATSIC).

Major geological terranes within the study region include parts of the Arunta Block, Ngalia Basin and Amadeus Basin. The region has significant high-relief basement ranges separated by relatively flat sandy plains with dunes. Low rainfall and high evaporation rates are dominant, and there are minimal surface water resources. Groundwater is critical for human consumption and pastoral activity. However, the paucity of water bores over much of the study area limits the available information on groundwater resources.

Wischusen (1998) identified six aquifer systems in the Western Water Study region:

- **The Amadeus system:** comprising Late Proterozoic to Palaeozoic sedimentary rock aquifers. These are highly productive aquifers to the east, for example, 12 x 10^6 m^3 of groundwater per-year is abstracted from the Mereenie Sandstone aquifer and used to supply Alice Springs (NRETA, 2006). However, the groundwater resources of these deep aquifers are poorly known from the Western Water Study region. The absence of large rivers in direct connection with the aquifers minimises their prospects for locally enhanced recharge and low salinity groundwater. Most bores are >100 m deep and, although yields may be significant, salinity is generally >1,000 mg/L TDS. Groundwater in these sedimentary rock aquifers is typically dominated by sulfate–chlorine–bicarbonate ions, with low nitrate levels.
- **The Ngalia system:** which consists mostly of Late Palaeozoic fractured sedimentary rock aquifers. These supply moderate amounts of potable groundwater from relatively deep bores at the Yuendumu community. The nature of this aquifer system is poorly understood in the study area; the groundwater composition is dominated by chlorine-bicarbonate-sulfate.
- **Mountain Front systems:** these are unconfined alluvial sand, gravel and clay aquifers that are hydraulically connected to other Cenozoic aquifers. Coarse-grained deposits were formed in high-energy environments adjacent to basement upland highs. High runoff and recharge rates have led to relatively large fresh groundwater resources. Bore yields are moderate (mean of 150 m^3/day) and salinity levels are relatively low (mean of 922 mg/L TDS). Groundwater composition is dominated by bicarbonate-chlorine-sulfate ions. Wischusen (1998) reported that the full extent of the aquifer system is poorly defined, and that the main zone near Papunya may extend further westward. Similar physiographic settings in central Australia may also contain similar aquifer systems. The main aquifer zone is interpreted to have a gradational northern boundary with other Cenozoic aquifers, although the nature of this contact is poorly defined. Groundwater quality probably improves with proximity to the mountain front recharge zone, and higher bore yields exist in coarser-grained sediments.
- **Cenozoic system aquifers:** are poorly understood because the full extent of Cenozoic basins and palaeovalley depositional systems is not well constrained; widespread Quaternary dunefields cover much of the region. The aquifers occur in alluvial and lacustrine sediments and near-surface calcrete. The Mount Wedge Basin contains Cenozoic aquifers, although the full extent and thickness of the basin aquifer sequence is poorly understood due to lack of drilling. A palaeovalley extending from 100 kilometres to the east of the study area across to Lake MacKay (Wilkinkara) has previously been mapped, e.g., Tickell, 2008. This palaeovalley crosses the centre of the Western Water Study area and is marked by a chain of playa lakes near Central Mount Wedge. Drilling in the palaeovalley has shown that clay- and sand-rich sediment lenses occur, suggesting that confined and unconfined aquifer conditions exist within the palaeovalley sequence. Groundwater from the palaeovalley is mostly brackish (mean of 3,178 mg/L TDS); bores are commonly high yielding (maximum of 2,760 m^3/day) and obtain groundwater from shallow to moderate depths (mean of 51 metres). Calcrete aquifers have higher salinity groundwater (mean of 5,579 mg/L TDS) and calcrete commonly borders playas and may extend along the palaeodrainage course. However, groundwater salinity levels in calcrete aquifers away

from playas may be lower, as is the case in the Amadeus region where calcrete groundwater salinity is <3,000 mg/L greater than 5 kilometres away from the Lake Amadeus discharge zone (Jacobson et al., 1989). Groundwater is typically chlorine-sulfate-bicarbonate dominated, which indicates long transit times and enhanced evaporative concentration and evolution from the original Mountain Front composition. Only minor amounts of potable groundwater are likely to occur in these systems, mainly in places where aquifers are proximal to ephemeral streams.

- **Playa systems:** these have highly elevated groundwater salinities due to evaporative discharge and salt concentration. The playas are Type E of Bowler's (1986) classification system (Section 2.8.1, Figure 2.6); they are groundwater-dominated and typically have >220,000 mg/L sodium-chlorine rich brines below the playas. Salinity levels can be considerably lower (<10,000 mg/L) within 15 kilometres of the playa margin. Playas are only covered by surface water during extreme rainfall events.
- **North and South Arunta systems:** these comprise fractured basement rock aquifers with low groundwater resources.

Hostetler et al. (1998) reported that 865 bores occur in the Western Water Study region; 75% of bores are for stock-watering and typically lack any drilling or monitoring records. Of 479 bores investigated during the study only 39 contained groundwater within potable standards outlined in the Australian Drinking Water Guidelines (1996). Groundwater in 317 bores exceeds 800 mg/L TDS, and of the bores with lower salinity levels 25% exceed nitrate (50 mg/L) and fluoride (1.5 mg/L) guidelines. Major ion concentrations (sulfate, chlorine, and sodium) have similar patterns to TDS levels, although the proportion of ionic species varies between different aquifer systems. High values for sodium occur in 41 of 120 drinking water bores, which is problematic due to the association of sodium with cardiovascular disease. Minor ions occur at lower concentrations, although some heavy metals may exceed guidelines such as boron (>0.3 mg/L) and uranium (>0.02 mg/L). The high levels of salinity and deleterious ions are due to limited recharge opportunities in modern times, high evaporation rates during recharge and long residence times in groundwater flow systems. A linear correlation between chloride and TDS in groundwater indicates that evapotranspiration is the major mechanism for groundwater evolution as the rocks have low chloride contents (Wischusen, 1998). High bicarbonate relative to chloride and sulfate in the fractured basalt aquifer at Kintore, and in mountain front aquifers near Papunya, indicates proximity to recharge and shorter groundwater residence times. High nitrate values are believed to be derived mostly from termite activity (Barnes et al., 1992). High fluoride and boron are derived from granitic rocks in the Arunta Block and from Cenozoic sediments derived from those sources. Excess fluoride can induce dental fluorosis and high boron is linked to gastro-intestinal disturbance and depression. Elevated uranium levels are also associated with Cenozoic sediments or granite in the Arunta Block. Hostetler et al. (1998) noted that poor health is associated with dehydration due to low palatability of groundwater, in addition to problems of high salinity and toxic elements. Accordingly, they suggested the development of dual water reticulation systems in affected communities, with drinking water supplied from reverse osmosis treatment or rainwater tanks and untreated groundwater restricted to other domestic purposes. They also suggested that widespread use of water coolers would ameliorate palatability problems.

A groundwater divide occurs at the northern Amadeus Basin boundary; groundwater to the north of this divide flows into the palaeodrainage system which falls to the west from 540 metres AHD at playas near Central Mount Wedge to about 360 metres AHD at Lake MacKay (Wischusen, 1998). South of the divide, groundwater flows to the Karinga Palaeodrainage which is marked by a long chain of playas termed the **Central Australian Discharge Zone** by Jacobson et al. (1988, 1989). Southwest of Kintore groundwater flow occurs in a tributary palaeovalley towards Lake MacDonald.

In the northern part of the study area, groundwater within the Ngalia aquifer system flows northwards to the Yaloogarie Basin. Groundwater travel times are very slow in the Amadeus and Ngalia sedimentary basin aquifers, ranging from 0.0042 to 0.1 metres-per-day). Flow rates are faster in the mountain front aquifer systems (about 3 metres-per-day) indicating that groundwater travel time is about 20,000 years from Papunya to Lake Ngalia near Central Mount Wedge. Groundwater in palaeovalley aquifers is probably of mixed origin, with older water from up-gradient throughflow in the main valley and younger water from inflowing tributaries along the valley sides.

In the adjacent Lake Lewis Basin, at the eastern edge of the Western Water Study area, radiocarbon (^{14}C) dating of groundwater in Late Cenozoic fluvial aquifers <50 metres below surface was undertaken by English (2002). Mainly Holocene groundwater occurs in these aquifers, with groundwater <4,000 years old present beneath the main creeklines and their immediate flood-out areas, and proximal runoff zones at the base of bedrock ranges. These relatively young groundwater systems represent the best quality water in the area, as defined by bicarbonate to chlorine ratios. Recharge occurs by concentrated runoff and overland flow following major rainfall events (English, 2002). Aquifers beneath interfluvial areas contain older Holocene groundwater, 4,000–8,000 years old, characterised by more diffuse and less frequent recharge. The Joker Palaeochannel underlies dunefields north of Papunya and is fed by Derwent Creek, which rises in headwater catchments of the Lake Lewis Basin. This palaeochannel, which flows north-west from the West MacDonnell Ranges towards Lake Ngalia and Central Mount Wedge, contains groundwater about 20,000 years old. It represents a shallow groundwater conduit directed away from the major discharge zone at Lake Lewis and, as such, it contains relatively old groundwater because playa discharge rates exceed thousands of years. The ^{14}C groundwater ages are very comparable with those obtained by Harrington et al. (1999) in Ti-Tree Basin to the north-east of Lake Lewis Basin. The Lake Lewis Basin has relatively dynamic recharge and discharge processes due to nearby high bedrock mountains (such as Mt Zeil that rises some 900 metres above the piedmont plain), ephemeral creeks and flood-out zones, debouchment of the major headwater catchments from the ranges, and the orographic effect of the ranges with respect to monsoonal incursions from the north (English, 2002).

As is typical for arid areas, groundwater recharge is highly episodic and difficult to quantify in this region. At Papunya, for example, it has not been possible to directly correlate rising groundwater levels with recharge (rain) events since records were first maintained in the 1960's. This indicates the high volume of groundwater storage near Papunya and provides no information on recharge processes occurring in mountain front aquifers or the transfer of groundwater to Cenozoic aquifers. However, runoff recharge has been observed in analogous situations such as the Alice Springs Town Basin (Section 4.3.5) and can therefore be inferred for high-magnitude rainfall/runoff events in the mountain front aquifers near Papunya. The slow groundwater travel time to Papunya (>1,000 years), which lies about 10 kilometres from the mountains, may attenuate the water-level response and limit direct observation of recharge. Stable isotope studies at Yulara (Barnes et al., 1992) and Ti-Tree (Harrington and Herczeg, 1998) have indicated an evaporation effect and minimal direct recharge in the modern environment. Wischusen (1998) proposed a recharge model that takes account of glacial/interglacial climate change over 100,000 year cycles (Figure 4.8). Under wetter interglacial conditions, the amount of evapotranspiration is less than direct recharge, and indirect recharge is high. Thus, mixed-source groundwater recharge occurs. Evapotranspired water and stored salts in the vadose zone, a legacy of prior drier climates, are flushed by direct recharge to the groundwater system – elevating salinity and contributing to an evaporated isotopic signature. Under more arid conditions like today, which are probably representative of the Quaternary, evapotranspiration exceeds direct recharge and the vertical flux is low (<0.1 millimetre-per-year), although localised and indirect recharge may still occur. The vadose zone becomes saline (chlorine levels >10,000 mg/L) and has an evaporated isotopic signature. This model demonstrates the long and complex history involved in groundwater recharge processes and the long residence times in the vadose zones. Wischusen (1998) also noted the potential for vegetation changes, such as occurred at the time of aboriginal occupation (Latz, 1995; Miller et al., 2005a, 2005b, 2007), to influence recharge processes.

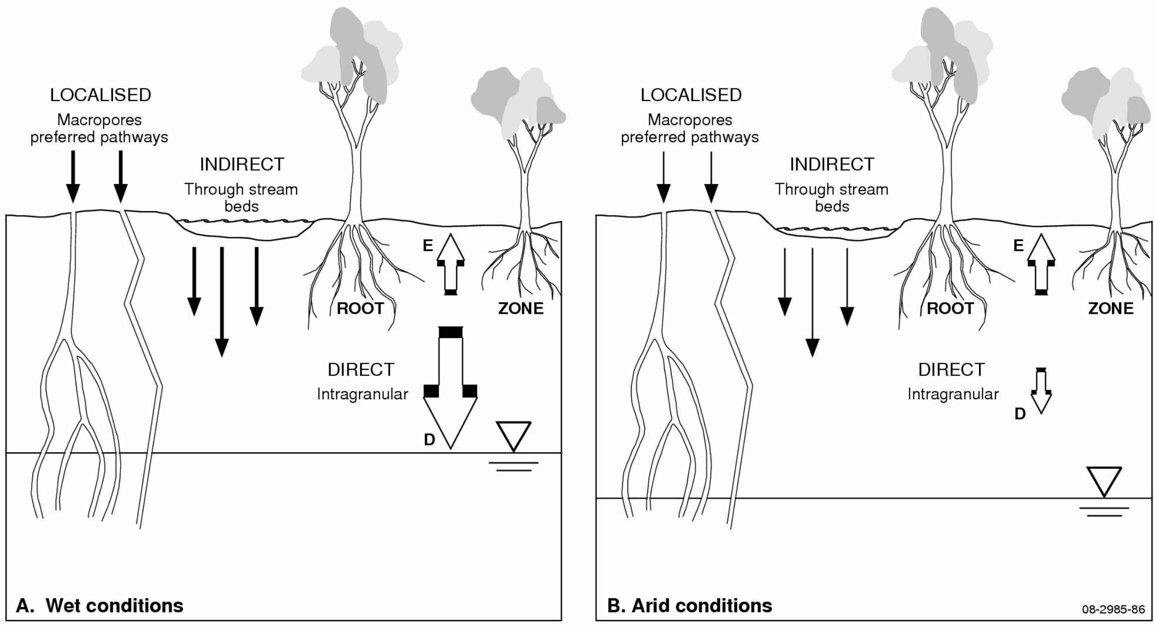


Figure 4.8: *Groundwater recharge model for the Australian arid zone, accounting for glacial (arid) and interglacial (wet) climate conditions. Figure is modified from Wischusen (1998).*

The long-term variability of recharge processes means that it is difficult to quantify recharge rates in arid zone aquifers; hence, sustainable groundwater yields are also difficult to determine. At many communities, such as Papunya, the ratio of extraction to storage is so low that small-scale abstraction is highly buffered, even if not demonstrably sustainable. However, the operation of any large-scale abstraction scheme (e.g., required to establish new horticulture enterprises) would require careful response-monitoring. At Yuendumu, where groundwater storage levels are relatively low, continued abstraction has effectively mined the resource and led to significant water-level decline because of the very slow recharge rate. Future relocation of water supply bore at Yuendumu may be necessary.

4.3.4. Lake Amadeus – Uluru Region

The lowland Lake Amadeus to Uluru region is an elongated west-north-west trending area of 90,000 km^2 bounded to the north by the Cleland Hills and the George Gill Range (up to 900 metres AHD) and to the south by the Musgrave and Petermann Ranges (up to 1,300 metres AHD). The region is part of the Proterozoic to Palaeozoic Amadeus Basin, and occurs in an anticlinal depression with a collapsed core due to solution of upthrust evaporate deposits (Jacobson et al., 1988, 1989). A Quaternary sand plain with dunes up to 30 metres high covers most of the depression and a linear chain of playas, in the lowest central axis, extends some 500 kilometres from Lake Hopkins in the west to the Finke River in the east. Low bedrock hills including prominent inselbergs such as Kata Tjuta (the Olgas), Uluru (Ayers Rock) and Atila (Mount Conner) rise out of the sand plain and dunes that cover the landscape between the ranges and the playas. In the modern environment, creeks from ranges to the north and south flood-out into the sand dunes and do not reach the playas. However, English (1998a) used remotely sensed datasets to identify a deltaic distributary braid-plain system north of Kata Tjuta towards Yulara Creek and Lake Amadeus. This drainage is mostly disrupted by the overlying dunes but is concordant with underlying palaeodrainage and still reflects the modern topographic gradient. The Quaternary dunes are at the centre of the continental-scale anti-clockwise dunefield whorl and are disorganised due to multi-directional wind patterns. Playas rarely hold surface water from direct high-magnitude rainfall events, for example, Lake Amadeus may have up to 5% of its surface area covered by water after 25 millimetres of rain and 10% after 50 millimetres, although this typically evaporates within days. After 100 millimetres of rainfall surface water can remain on the playas for weeks. Within the lowland depression a topographic divide occurs at about 480 metres AHD just east of Lake Amadeus, with an internal basin to the west centred on Lake Neale at 440 metres AHD and an easterly down-gradient to 345 metres AHD at the Finke River junction. The region has an arid climate with about 250 millimetres of mean annual rainfall. The rainfall pattern is summer dominated and highly variable, ranging from <100 millimetres to >900 millimetres, e.g., heavy rains in 1974. Individual rainfall events > 25 millimetres occur three times per year on average.

Van der Graaff et al. (1977) interpreted a palaeovalley oriented south-east through Lake Amadeus towards Lake Eyre. Borehole data from Jacobson et al. (1988, 1989) supported that concept and they proposed the name Karinga Palaeoriver. However, the actual palaeoriver course is uncertain over much of its extent, and the widespread occurrence of basal clay and lignite sediments suggests that swampy or lacustrine conditions were common in the early depositional history. An isopach map of Cenozoic palaeovalley deposits compiled from bore data by Jacobson et al. (1988) indicated that the deepest part of the palaeovalley (thalweg) lies just south of Lake Amadeus and is close to the playa chain near Curtin Springs (Figure 4.9). These isopachs indicate 10–20 metres shallowing of the contact between basement rocks and Cenozoic sediments and a tight north–south constriction in the palaeovalley close to Curtin Springs. Constriction of the palaeovalley and the occurrence of a nearby modern topographic high imply probable tectonic disruption of the palaeovalley. The isopach map has also been used to identify palaeotributaries in the south, including one between Curtin Springs and Atila and another near the modern Britten Jones Creek east of Uluru. From limited borehole information, Jacobson et al. (1988) mapped the Dune Plains Palaeovalley as flowing north-east between Uluru and Kata Tjuta then turning east to join with the Britten Jones Palaeovalley, which itself trends northwards towards Lake Amadeus and joins the trunk Karinga Palaeovalley. However, English (1998b) demonstrated that both the modern drainage and palaeodrainage systems curve around Kata Tjuta through the Dune Plain then trend around the eastern margin of the Sedimentaries before continuing north-north-west to the head of Yulara Creek and then to Lake Amadeus.

4.3.4.1 Lake Amadeus – Uluru Region Groundwater Resources

Lake Amadeus is the largest in the chain of playas which forms the discharge zone for groundwater sourced from the valley-margin highlands and which flows through both Cenozoic aquifers and the underlying Proterozoic rocks. Jacobson et al. (1988) named this system the Central Australian Groundwater Discharge Zone. Potentiometric contours for the local watertable indicate that a groundwater divide coincides with the topographic high near Curtin Springs, to the east of Lake Amadeus.

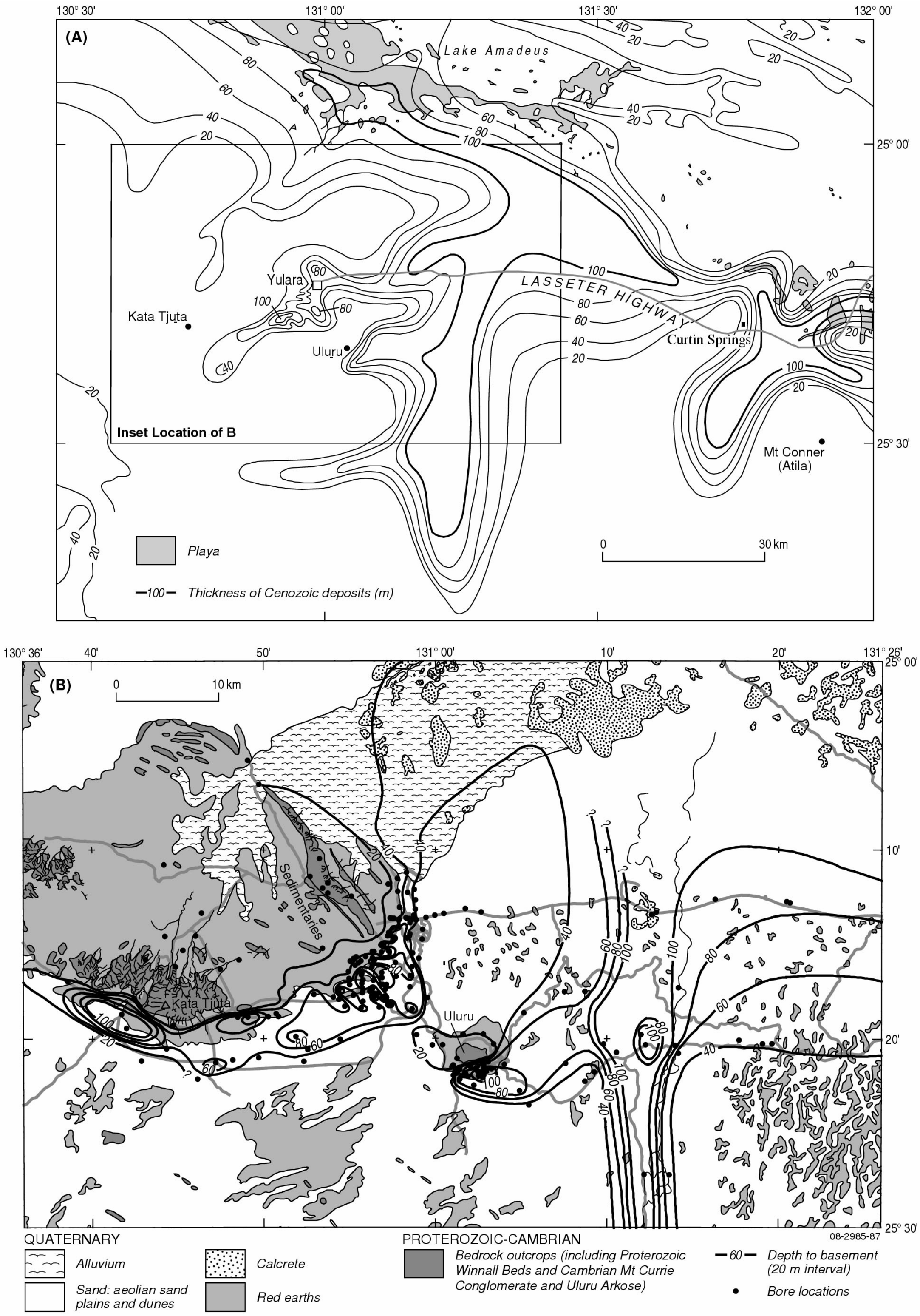


Figure 4.9: *(A) Isopach map of Cenozoic sediment deposits in the Lake Amadeus to Uluru region of central Australia, (B) Detailed surface geology map around Uluru with depth-to-basement contours showing the thickness of Quaternary sand deposits. The location of groundwater bores around Uluru is also shown on this map. These figures are modified from Jacobsen et al. (1988) and English (1998).*

Jacobson et al. (1988; 1989) provided a detailed study of the groundwater processes in the Lake Amadeus and Curtin Springs area. The Lake Amadeus playa brine pool is dominated by sodium-magnesium-chlorine brines with mean TDS of 250,000 mg/L. Jacobson et al. (1989) estimated that the total salt stored in these playas is 6 x 10^9 tonnes, representing 12,000 years accumulation as (salt balance calculation). Water balance calculations at Spring Lake near Curtin Springs indicated total evaporative losses at 275 millimetres-per-year, consisting of 225 millimetres of direct rainfall and 50 millimetres of groundwater discharge. Jacobson et al. (1989) extrapolated this figure over the entire playa area to derive the total discharge amount. These calculations indicated only 1 millimetre-per-year recharge (or 0.4% of total rainfall) if balanced by recharge averaged over the entire basin surface. Recharge here mainly occurs by:

- Infiltration through rock fractures in the hills flanking the basin;
- Indirect recharge through river floods and loss through sandy beds;
- Direct infiltration where sand cover is thin; and
- Direct infiltration through calcrete, which is the most important mechanism (Jacobson et al., 1989).

At Curtin Springs, mounded calcrete deposits are up to12 metres thick, with the watertable at 4–6 metres below surface and relatively fresh groundwater (1,500 mg/L TDS) overlying more saline water at depth. Groundwater in the calcrete aquifers has measurable tritium and relatively young (hundreds of years) ^{14}C ages, indicative of an active recharge system. Groundwater flows from the palaeovalley margins to the playa zone and then along the trunk palaeovalley to the east; complex groundwater flow paths and chemical evolution occurs between individual playas. Groundwater salinity increases gradually along palaeovalley flow paths, then more rapidly close to playa discharge zones. Fresher recharge waters (up to 1,500 mg/L TDS) are dominated by bicarbonate and chlorine ions, with sodium and calcium the most abundant cations. Bicarbonate and calcium ions are removed early in the evolution of these groundwater systems by the precipitation of calcrete. Hence, more saline groundwater (1,500–15,000 mg/L TDS) is dominated by chlorine, sulfate and sodium ions. At very high salinities (>100,000 mg/L TDS) gypsum precipitates and sulfate and calcium are removed from solution. The residual groundwater is thus chlorine-rich brine with sodium, potassium and magnesium cations. Glauberite (Na–Ca sulfate) can also precipitate in some playas and halite forms thin playa salt crusts. Evolved groundwater is commonly high in silica, which may lead to precipitation of siliceous calcrete. Nitrate, fluoride and iron commonly exceed drinking water guidelines, even in low salinity groundwater. For instance, many calcrete aquifers in the Lake Amadeus region contain large volumes of relatively fresh groundwater, but with elevated nitrate levels and low bore yields.

Palaeovalley evolution and groundwater resources in the Uluru – Kata Tjuta region of central Australia have been described by English (1998a, 1998b). This area is at the northern edge of the Proterozoic Musgrave Province and the southern edge of the Amadeus Basin. The arkose and conglomerate rock units which form Uluru and Kata Tjuta (respectively) were derived from the Musgrave Province during erosional events in the Cambrian. Palaeovalley sediment aquifers provide the main water source for the Yulara tourist resort and the Mutitjulu aboriginal community. In 1998 about 3 x 10^5 m^3-per-year of mostly brackish groundwater was used at Yulara (1,500–2,100 mg/L TDS), requiring treatment by reverse osmosis for human consumption. Untreated water was used directly for irrigation, some domestic purposes and fire-fighting. Waste water from the resort is treated and used for irrigation. The buried Dune Plains Palaeovalley between Uluru and Kata Tjuta is about twenty kilometres long and five kilometres wide. It forms a closed, arc-like valley at depth with multiple deeper troughs and elevated ridges (dome-and-ridge topography). Discrete depressions occur south of both Kata Tjuta and Uluru (in a lateral tributary of the Britten Jones Palaeovalley), extending (respectively) to depths of 100 metres and 40–50 metres below the palaeovalley outlet sill north of Yulara. These depressions were originally lakes within the palaeovalley system, with deposition of alluvial fan and lacustrine sediments commencing in Maastrichtian times (Twidale and Harris, 1991; Macphail, 1997). These lakes are interpreted to have filled with sediment prior to the onset of widespread fluvial conditions in the palaeovalley which deposited the facies that forms the present-day, heavily utilised aquifers. The potentiometric surface shows steep watertable gradients in the arcuate Dune Plains Palaeovalley, which levels out and becomes more complicated near an interpreted lateral and vertical bedrock constriction at Yulara. Groundwater salinity increases at this constriction, perhaps due to sluggish flow velocities, as the potentiometric gradient is very shallow further north. However, flow rates are also influenced by variations in the transmissivity and dimensions of the aquifer, e.g., higher flow rates in wider sections of the palaeovalley.

The Dune Plains Palaeovalley contains a heterogeneous stratigraphic sequence and has a relatively short flow path. Groundwater is young (^{14}C ages range from modern to 8,720 years old and cluster between 770 and 5,000 years before-present) indicating that recharge is sporadic in the modern climate regime due to irregular high-magnitude rainfall events (English, 1998a). Hydrogen and oxygen stable isotopes of groundwater plot below the meteoric water line indicating the importance of evaporation during recharge processes. Barnes et al. (1992) suggested a 130 millimetre rainfall-event threshold for effective direct recharge, but English (1998a) suggested that this figure may be too low as 142 millimetres of rain which fell over five days in February 1997 had little impact on groundwater levels (as measured in bores). Either the threshold value or the rainfall intensity (or both) must be higher. English (1998a) also postulated that the run-on/runoff sheetflow landforms common on the mulga patterned terrain of the region, which are produced by episodic floodwaters across aprons around inselberg outcrops, may significantly enhance local recharge. These landforms comprise red earth soils and underlying calcrete sheets and support banded mulga vegetation. Sheetflow-related recharge maximises water conservation and infiltration to underlying aquifers during rainfall and run-off events (English, 1998a).

4.3.5. Alice Springs Town Basin and Inner Farm Basin

The climate at Alice Springs is arid with about 270 millimetres mean annual rainfall. Rainfall patterns are irregular, although slightly more common in summer, and is considerably less than the amount of evaporation. There is also wide annual and diurnal temperature range.

Three inter-connected alluvial basins occur along the Todd River near Alice Springs:

- **The Alice Springs Town Basin**, a small Quaternary alluvial basin which covers an area of about eight square kilometres to a depth of 22 metres and underlies the township.
- **The Inner Farm Basin** located south of the Heavitree Range and connected to the Town Basin through the Heavitree Gap.
- **The Outer Farm Basin,** south of the Blatherskite Range and connected to the Inner Farm Basin through the Blatherskite Gap and east of Mount Blatherskite where the present Todd River course lies.

The main source of natural recharge for all three basins is derived from episodic flows in the Todd River, concentrated in specific areas of the river bed. The stratigraphic sequences of the Inner and Outer Farm Basins are more complex than the Quaternary Town Basin and both contain older

Cenozoic sediments, e.g., Palaeogene (Quinlan, 1967; Quinlan and Woolley, 1969). The Outer Farm Basin is the largest and deepest of the three basins and has up to 300 metres of lacustrine clays, overlain by about 25 metres of Quaternary fluvial sediments. A Quaternary palaeochannel, divergent from the Todd River, occurs in the Inner Farm Basin and passes west of Mount Blatherskite (Blatherskite Gap) to the Outer Farm Basin where it lies south of the existing river bed (Jeuken, 2004). The western portion of the Inner Farm Basin is the site of the Alice Springs sewage treatment plant which consists of three ponds (A, B and C) constructed between 1961 and 1991. Treated effluent is variously discharged either south to Ilparpa Swamp, or east to irrigate Blatherskite Park (from A pond) or a forestry plot (B pond) (Berry, 1991). Effluent discharge, as well as leakage from the ponds, potentially impacts on the quality of groundwater in the basin aquifers. A soil aquifer treatment (SAT) scheme, located in the Outer Farm Basin, is proposed to replace the current Alice Springs sewerage treatment discharge (Knapton et al., 2004).

The Town Basin was formerly used to supply Alice Springs with potable water, with total aquifer storage estimated between 1.5 x 10^6 m^3 to 5 x 10^6 m^3 (Quinlan, 1961). In 1964 groundwater abstraction was 1.14 x 10^6 m^3, with significant water-level decline already evident by then. A bore from the Inner Farm Basin was used to supplement the town water supply between January 1964 and April 1965 before the Roe Creek borefield was constructed in the Palaeozoic Meerenie Sandstone. This new borefield is still used to supply Alice Springs with potable water.

Fluvial sediments in the Town Basin overlie Precambrian basement rocks. Thin and irregular sand lenses form five recognised aquifers which are recharged by flow from the Todd River (Quinlan and Woolley, 1969). The water level in each of the Quaternary aquifers fluctuates in response to both recharge and abstraction, with the recharge response mainly dependant on distance from the river. Todd River runoff is highly episodic and depends largely on high-magnitude rainfall events. Wilson (1958) estimated initial recharge rates as 8,800 L/m^2 declining to 25 L/m^2 within 24 hours. The rate of recharge declines in the first few days due to swelling of the clay minerals in the aquifer matrix, then increases as entrapped air is dissolved by infiltrating water. However, floods probably never last long enough to completely dissipate the entrapped air. Within the Quaternary aquifers groundwater moves freely where channel sands are interconnected, but a recharge mound which forms near the river requires three months to fully dissipate before recharge can subsequently recur. Groundwater abstraction between 1958 and 1964 significantly reduced water levels, but did not lead to increased recharge. This suggests that the rate of transfer from the recharge mound is slower than the rate of groundwater flow in the aquifers. In 2006 abstraction from the Roe Creek borefield was about 12 x 10^6 m^3-per-year, whereas total groundwater use from the Town Basin (for irrigation of sports grounds and open spaces) was about 0.8 x 10^6 m^3-per-year (NRETA, 2006). Significant recharge of the Town Basin aquifers occurred in the early 1970's, especially 1974 when the Todd River ran for about 300 days. This caused significant watertable rise which was further exacerbated by infiltration of water used for garden irrigation (sourced from the Roe Creek borefield). Read (2005) estimated that non-pumping and non-outflow losses from the Town Basin, in periods of no recharge, were proportional to evapotranspiration and averaged 173 x10^3 m^3-per-year, corresponding to a rate of watertable decline of about 0.3 metres-per-year. Mobilisation of salts in association with the rising watertable has caused localised salinity problems, and recharge of lower salinity water has been inhibited by the higher watertable (NRETA, 2006).

The measured salinity of Todd River floodwater is 65–202 mg/L with variable ionic abundance. Groundwater salinity in the Quaternary fluvial aquifers of the Town Basin is 250–3000 mg/L, increasing with depth and distance away from the Todd River. Rising salinity levels correspond with changes in the chemical composition of the groundwater, from bicarbonate-dominated through a zone of mixed anion abundance, and eventually to chloride-dominated. Sodium is generally the most abundant dissolved cation in these aquifers.

The stratigraphic and hydrogeologic composition of the Inner Farm Basin is more complex than the Town Basin. Aquifers occur in older Cenozoic sediments (e.g., Palaeogene and early Neogene deposits) and in deeply weathered basement rocks, as well as in Quaternary Todd River alluvium (Quinlan and Woolley, 1969). Seismic profiles by Dyson and Wiebenga (1957) indicated significantly different depths to the basement weathered zone between the Town and Inner Farm Basins, interpreted by Quinlan and Woolley (1969) to indicate probable different formation ages. Groundwater abstraction from the Inner Farm basin commenced in 1942, and was used to supply irrigated market gardens and a piggery. Waterbores were later constructed for road building (non-potable water) and for the Alice Springs town water supply.

Older Cenozoic (Tertiary) sediments have limited spatial distribution in the Inner Farm Basin but are continuous with more extensive deposits in the Outer Farm Basin further south (Quinlan and Woolley, 1969). Up to 13 metres of deeply weathered basement material underlies the Tertiary sediments of the Inner Farm Basin, which have a maximum thickness of 45 metres near the southern margin. The earliest Cenozoic mud and lignite sediment in the Inner Farm Basin is believed to be lacustrine in origin. White to pale grey, fine sandy clay commonly mottled reddish-brown and yellow, is the dominant sediment type. Variably coloured clay, silty clay–clayey silt and fine- to coarse-grained sand also occur. Pale, angular to subangular quartz sand ranging from fine- to very coarse-grained is also a minor component of some well sorted interbeds which are generally <3 metres thick. Some polymict sands, similar to the Quaternary fluvial sediments, occur in the upper part of the sequence but these are more common in the Outer Farm Basin. In places where the Tertiary sediments outcrop well-developed weathering profiles, which include a 3–6 metre thick silcrete cap over a pale leached zone, mostly obscure the composition of the sediments. Less silicified zones up to 1.5 metres thick, underlain by coarse- to very coarse-grained angular quartz sand, occur at the top of the Tertiary sequence beneath the Quaternary sediments. Berry (1991) reported that older Cenozoic sediments are absent from the western portion of the Inner Farm Basin.

Quaternary sediments within the Inner Farm Basin are fluvial deposits of the Todd River and are up to 27 metres thick. There is no direct correlation between the thickest alluvial sediments and the location of the present river channel. The Quaternary sediments are a mixture of gravel, sand, silt and clay. The sand-rich beds (about 15% of total composition) commonly form elongate and narrow lenticular channel deposits which anastomose vertically and horizontally; this makes it difficult to correlate the basin stratigraphy. Brown, clay-rich sand and silty clay deposited in floodplain back swamp and overbank environments are the most abundant sediment types. The sediments are more poorly sorted towards the southern margin of the basin, resulting in lower permeability and porosity (Quinlan and Woolley, 1969). Quaternary sediments in the western part of the basin include the main palaeochannel which has a maximum thickness of 28 metres at Bore RN 15899, consisting of 14 metres of fine-grained, very poorly supported silty sediments overlying moderately sorted sandy gravels (Berry, 1991). The Quaternary sequence becomes thinner and consists of finer-grained sediments away from the palaeochannel.

4.3.5.1. Groundwater Resources of the Inner Farm Basin

Groundwater resources in the Quaternary fluvial aquifers of the Inner Farm Basin are poorly understood but are believed to be similar to those of the Town Basin. Groundwater mainly occurs in permeable channel sands and recharge is derived from Todd River runoff combined with outflow from the Town Basin (Quinlan and Woolley, 1969). This outflow component consists of:

- Groundwater with salinity >1,000 mg/L TDS, with mixed ionic concentrations, which moves through deeper aquifers on the western side of the basin; and
- Shallower groundwater on the eastern side of basin, which mixes with recharge from Todd River runoff.

Quinlan and Woolley (1969) identified two older Cenozoic (pre-Quaternary) aquifer systems in the Inner Farm Basin:

- Clean quartz sand beds <3 metres thick which have bore yields of up to 330 m^3-per-day. These sand units are not readily correlated between bores. They are most common in the south-east part of the basin.
- Deeply weathered bedrock horizons developed on buried strike ridges of brecciated dolomitic limestone and siltstone of the Bitter Springs Formation. The combination of weathered and fractured bedrock acts as a single aquifer system, commonly with greater storage capacity than the Cenozoic sediment aquifers.

There are limited opportunities for groundwater recharge and throughflow in both aquifer systems and this is reflected in their chemical composition. Shallow Quaternary aquifer groundwater with high bicarbonate levels enters the northern basin on the eastern side, and deeper mixed-ion groundwater enters on the western side. Water level fluctuations in the Inner Basin Quaternary aquifers, in response to Todd River flow, are similar to the Town Basin. The salinity of the bicarbonate-dominated groundwater does not greatly change but sulfate and chloride concentrations increase as groundwater evolves to mixed-ion compositions. Sodium is the dominant cation close to recharge areas. However, the process which leads to the existence of two distinct groundwater compositional types in the Inner Farm Basin – one dominated by sodium and calcium and one with mixed cations – is not well understood. Intermixing with groundwater in the bedrock Bitter Springs Formation increases the abundance of sulfate and chloride in the Inner Farm Basin aquifers. In particular, the lower piezometric surface (caused by continued groundwater abstraction since 1957) has allowed ingress of sulfate-rich water from pyritic rocks in the Bitter Springs Formation. In the south of the basin, gently dipping Tertiary aquifers are truncated by Quaternary aquifers and this allows recharge of relatively low-salinity groundwater into the older aquifers, which flows down-dip with little change in composition. The location of this connected zone within the Inner Farm Basin, which links the Quaternary aquifers and the eroded top of the older Cenozoic aquifers, is inferred from analysis of hydrochemical data (Quinlan and Woolley, 1969).

The water level within the older Cenozoic aquifers does not directly correlate with flow in the Todd River, indicating that these aquifers have impermeable boundaries to the west, east and south. Bore interference caused by pumping from adjacent bores and increased groundwater withdrawal in the Town Basin is also common in the Inner Farm Basin. However, pump tests had not been undertaken in the Inner Farm Basin when Quinlan and Woolley (1969) first described the basin. Subsequently Berry (1991) reported on pump testing of bores in the Quaternary aquifers of the western Inner Farm Basin.

4.3.6. The Ti-Tree Cenozoic Basin

The Ti-Tree Basin lies 200 kilometres to the north of Alice Springs and covers approximately 5,500 square kilometres (Figure 4.10). Rainfall across the basin is highly variable and summer-dominated, with mean annual rainfall <300 millimetres, e.g., average of 290 millimetres-per-year across 45 years of monitoring at Aileron. Evaporation rates in this arid region are very high, with mean pan evaporation about 3,800 millimetres. Because of the importance of groundwater-irrigated horticulture in the basin the Ti-Tree Water Control District extends 14,000 square kilometres over the entire basin and surrounding catchment. Crops include table grapes, asparagus, mangos, melons, and cut flowers. In 2002 about 300 hectares was irrigated with 2.5 x 10^6 m^3 of groundwater, with further expansion likely in the future. In comparison, groundwater abstracted for local town and community water supplies totalled 12 x 10^4 m^3 in 2002. The existence of groundwater resources in the area which were potentially suitable for irrigated horticulture was known since the early 1960's, although the concept of a single large groundwater basin did not emerge until the late 1970's. This idea was later confirmed by the first major groundwater drilling program in 1980. McDonald (1988) undertook a detailed investigation of the stratigraphy and groundwater resources of the basin and much of the following description comes from that source.

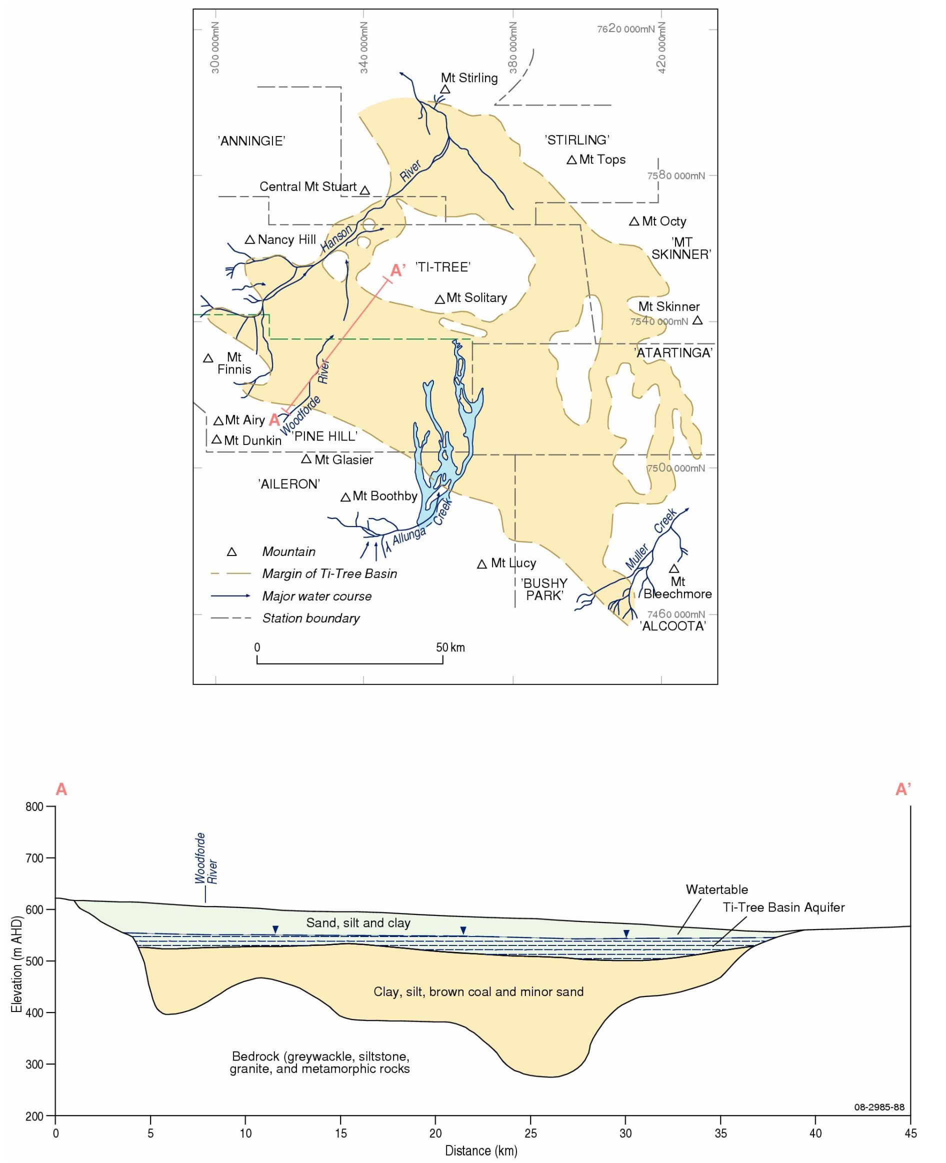


Figure 4.10: *Map of the Ti-Tree Basin in central Australia showing the location of surface drainage features, prominent mountains and pastoral station boundaries. The lower cross-section (A–A') is a schematic representation of the regional stratigraphic sequence of the basin, highlighting the main Ti-Tree aquifer system in the uppermost sand, silt and clay unit.*

The landscape of the Ti-Tree Basin consists of bedrock hills surrounding extensive sand plains with longitudinal dunes oriented north-west. Vegetation is mainly spinifex and various small trees and shrubs. A zone of less sandy soil surrounds the sand plain and forms an apron to the bedrock hills, which include the Reynolds Range to the south-west and the Hann Range to the north-east. Most of the modern drainage system terminates at the level of the plain, except for the Hanson and Woodforde Rivers near the western margin which exit towards the north. Calcrete deposits associated with shallow watertable levels are common in the northern basin, possibly formed along a prior course of the Woodforde River before diversion to the north to join the Hanson River. Geologically the Ti-Tree Basin is a Cenozoic continental basin with more than 300 metres of sediment infill overlying a complex suite of older metamorphic rocks including:

- Proterozoic granite, gneiss, orthogneiss, schist, amphibolite, granulite and quartzite of the Arunta Block. These rocks have complex metamorphic, tectonic and intrusive histories, and now underlie the basin and outcrop along parts of the margin. Most of these rocks are deeply weathered, and ferricrete occurs on the eastern margin.
- To the south, siltstone, sandstone and quartzite of the eastern Ngalia Basin forms part of the catchment.
- Proterozoic and Cambrian rocks of the Georgina Basin, including sandstone and siltstone formations, unconformably overlie the Arunta Block and form the northern and north-western catchment area. These rocks also underlie the basin outlet.

Mild tectonic uplift and erosion resulted in peneplanation and deep weathering of the basement rocks to depths of about 40 metres below surface. Secondary deposits of silcrete and ferricrete were also formed, and ferricrete is underlain by typical mottled and pallid zones.

Cenozoic deposition in the basin probably commenced in the Eocene. Green and grey, lacustrine mud deposits which lack bedding formed in low-energy reducing conditions (McDonald, 1988). These mud deposits are commonly lignite-bearing (NRETA, 2007). Senior (1972) suggested that the age of deposition was Early Tertiary. Mid-Tertiary weathering led to minor lithification and the formation of ferricrete within some parts of the lacustrine mud sequence. Overlying the basal mud deposits are interbedded chalcedonic limestone, sandstone, siltstone and minor sandy conglomerate; chalcedony is thought to have formed from direct silica precipitation contemporaneous with interbedded clastics (Senior, 1972). These sediments outcrop on the eastern and south-eastern basin flanks and are correlated to the Waite Formation within the Waite Basin (further to the south-east). The Waite Formation coarsens upwards, representing a change from lacustrine to fluvial conditions in the Ti-Tree Basin as the climate became subtropical, probably in the Late Miocene to Early Pliocene. O'Sullivan (1973) reported Mid Miocene plant microfossils from cores in the west of the basin. McDonald (1988) recognised three sub-units of undifferentiated Cenozoic alluvial sediments, which occur stratigraphically above the Waite Formation. These outcrop in the south-east of the basin and are also known from drilling (cores) in the basin centre, and include:

- A basal unit of multi-coloured, mottled, silty sandstone, which is partly micaceous and has pebble or granule conglomerate near the base;
- A middle unit of varicoloured, slightly silty sandstone, thinner than the upper unit and containing muscovite in the silt bands; and
- An upper unit of red-brown, slightly calcareous, silty sandstone, which has common limonite staining developed on joint planes.

This undifferentiated alluvial unit is associated with calcrete in areas where the watertable is relatively shallow. Deposition of later Cenozoic sediments was followed by uplift in the south and reversal of the drainage pattern to the north. Quaternary sand sheets and dunes cover much of the basin. Colluvium, scree and alluvium occur on the range flanks and are associated with modern watercourses.

4.3.6.1. Groundwater in the Ti-Tree Basin

McDonald (1988) summarised the groundwater resources of the Ti-Tree Basin from previous work and also reported on a detailed investigation of the central portion of the basin, where irrigated horticulture had not yet commenced. This included an extensive drilling program undertaken in 1984–1985.

Weathered and fractured basement rocks of the Arunta Block yield small quantities of variable quality groundwater. Waterbores drilled into rocks of the Ngalia Basin (e.g., the Vaughn Springs Quartzite) and Georgina Basin (e.g., the Central Mount Stuart Formation), underlying the Ti-Tree Basin catchment, are generally less successful than those which tap aquifers in the Arunta Block. The Lower Cenozoic lacustrine mud and silt deposits of the Ti-Tree Basin are not regarded as aquifers. Much of the outcropping Waite Formation in the west of the Ti-Tree Basin is above the level of the watertable. In the centre of the Ti-Tree Basin, bores sunk into chalcedonic limestones, which are presumed to be Waite Formation equivalents, have maximum groundwater yields of 3,450 metres^3- per-day. The coarser-grained sands, silty sands and gravels of the upper undifferentiated alluvial sequence are widespread and contain thin high-yielding aquifers (>2,500 m^3-per-day). Calcrete deposits in the northern part of the basin are also local aquifers, but Quaternary aeolian sediments are generally above the watertable.

McDonald (1988) presented potentiometric contours for the Ti-Tree Basin (Figure 4.11). These were derived from contemporaneous (1986) water level monitoring of a widespread bore network. Groundwater generally flows south to north, although it is complicated in places by the shape of the basin, e.g., flow tends to diverge around basement inliers and an elongated north-trending zone of high-permeability (interpreted as a depression or channel) runs through the centre of the basin to the northern outlet. Groundwater mounds, indicative of recharge, are associated with the Woodforde River, Allungra Creek and runoff zones from the eastern bedrock hills. The standing-water level indicates a groundwater gradient extending from 50 metres deep near the southern margins to less than 10 metres deep over the northern part of the basin (Figure 4.11).

Groundwater quality varies slightly across the Ti-Tree Basin (Figure 4.12). Commonly, the water quality within a single bore will also vary both temporally and with depth. The amount of total dissolved solids (TDS) in Ti-Tree groundwater ranges from 420–6,410 mg/L. Groundwater with TDS <1,000 mg/L extends north from each of the three main recharge mounds to a broad zone at the northern margin of the basin (south of the Mt Solitary inlier) and also extends further north into the basin outlet channel. Chloride contents range from 16–2,710 mg/L. McDonald (1988) showed that low-chloride groundwater, when mapped in two concentration (<100 mg/L and 100–200 mg/L) has a similar distribution to low TDS levels. The ratio of bicarbonate to chloride is interpreted by McDonald (1988) as an indicator of recharge; values >1 are closely correlated with low levels of TDS and low-chloride concentrations. High nitrate values from natural sources are typical of many central Australian groundwater systems and generally range from 70–350 mg/L in the Ti-Tree Basin, although an extremely high value of 812 mg/L has been recorded from one bore. Potable water supplies (with TDS of <1,500 mg/L and nitrate levels <45 mg/L) only occur in the north-west of the basin. The Ti-Tree township and the Pmara Jutunta aboriginal community both obtain their potable water supplies from the Ti-Tree Basin aquifer.

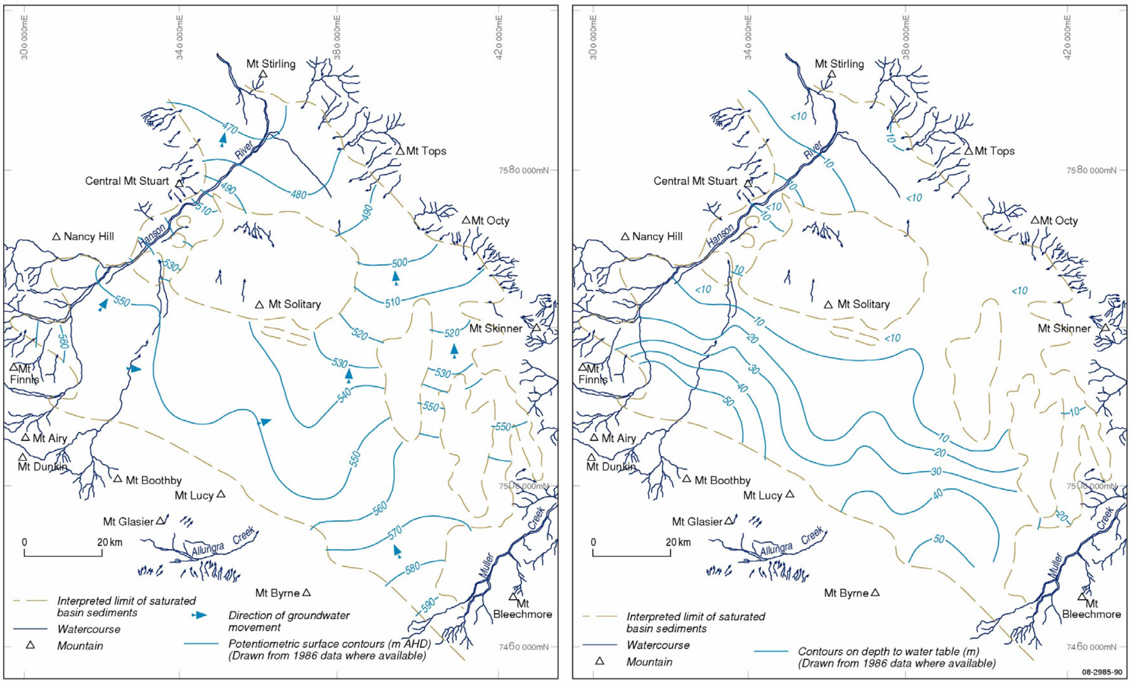


Figure 4.11: *Groundwater maps of the Ti-Tree Basin showing (at left) the direction of groundwater flow as derived from potentiometric contours and (at right) the depth to the standing-water level across the basin. Across the basin the groundwater system flows from south to north, with about 40 metres variation in depth to the watertable.*

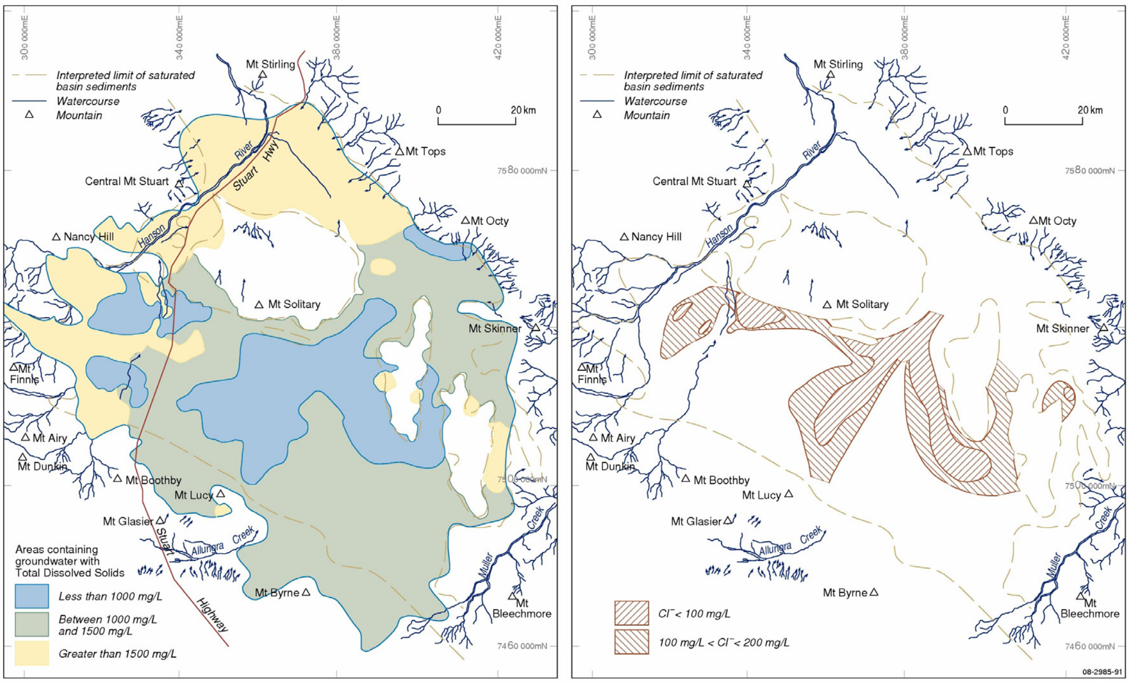


Figure 4.12: *Groundwater quality maps for the Ti-Tree Basin, highlighting the spatial variability of potable and brackish water zones. Isolated parts of the central and western Ti-Tree Basin generally have the freshest groundwater (<1,000 mg/L TDS), and these correspond with the lowest chlorine concentrations.*

High-magnitude rainfall and runoff events result in considerable flow across the basin in flood-out areas and in the Hanson and Woodforde rivers (Figure 4.10). High rainfall events are the main recharge mechanism for groundwater systems in the Ti-Tree Basin, e.g., Reinhard (1977) estimated 12 x 10^6 m^3 of recharge to the groundwater system, based on water level rises recorded in bores after major rainfall events. Recharge in the basin is mostly concentrated in three areas:

- The western portion of the basin, representing overflow of the Hanson and Woodforde rivers;
- The central portion of the basin north and north-east of Mt Lucy, representing flood-out of the Allungra Creek; and
- The eastern margin of the basin (western part of Atartinga Station) where overland flow accumulates in the basin from runoff sourced from adjacent basement rocks.

By contrast, in the south-east of the Ti-Tree Basin the Muller Creek captures most of the runoff derived from the adjacent bedrock hills, directing the water north-east to the Sandover River. Consequently there is no recharge mound in this part of the basin.

In the northern portion of the basin, groundwater is potentially discharged by evapotranspiration where widespread acacia shrubs access the relatively shallow watertable. This is reflected in the higher salinity groundwater which occurs here, despite the potential for local recharge (runoff) sourced from adjacent bedrock hills of the Mt Solitary inlier. NRETA (2007) recognised evapotranspiration in the north as the major discharge mechanism but also recognised groundwater exiting the basin through the palaeovalley at the north-east margin. NRETA (2007) also suggested that some of this outflow may discharge by evaporation at Stirling Swamp, downstream in the palaeovalley. However, Stirling Swamp is dominated by surface water processes and lacks many features typical of significant evaporative discharge, such as a salt crust and sub-playa brine pool. These factors suggest that no significant evaporative discharge of outflow from the Ti-Tree Basin groundwater system occurs at Stirling Swamp; rather, Stirling Swamp is probably perched above the level of groundwater outflow along the Hanson Palaeovalley. Additionally, despite demonstrating preferential groundwater flow into the north-eastern palaeovalley, McDonald (1988) did not consider this as a groundwater discharge route.

McDonald (1988) considered that all three low-salinity recharge mounds have potential for irrigated horticultural enterprises to be developed, although he recommended that the western area not be further exploited so as to protect existing horticulture near Ti-Tree township, and the water supplies for Ti-Tree and Pmara Jutunta. However, the central and eastern (Atartinga) groundwater zones were recommended for further detailed investigation of their irrigated horticulture potential.

4.3.6.2. The Central Ti-Tree Basin

The central, low-salinity (<1,000 mg/L) recharge mound of the Ti-Tree Basin was investigated in detail during 1984–1985. Some 14 waterbores, drilled to depths of 22–97 metres, terminated in the Lower Cenozoic lacustrine mud unit or in high water-producing zones which caused the drillholes to collapse. Bores were then pump tested and a second stage of drilling (12 bores) concentrated on a potential horticultural site selected on the basis of the initial results.

Stratigraphic analysis recognised a gradational boundary between the lower lacustrine mud unit and the overlying oxidised fluvial silty sands. The previously recognised three-part subdivision of the fluvial sequence was confirmed, but the boundaries between sub-units were unclear. Chalcedonic limestone, presumably equivalent to the Waite Formation, was identified in a number of bores, forming highly transmissive water-bearing zones underlain by sand either at or below the watertable. Silica replacing calcrete in palaeochannel sands probably formed due to precipitation from groundwater. The basin sequence thins towards the north-east due to topographic lowering of the basin surface and shallower basement depths. The lacustrine unit is also thinner towards the north-east and is absent in the eastern part of the basin. The main aquifer unit is of fluvial origin and was sourced from a granitic or metamorphic terrane, with indications of transport towards the east and channel migration across the basin; this causes a high degree of vertical and horizontal variability in the nature of the sequence. The main aquifer unit is about 50 metres thinner at the north-east of the basin, compared to the southern part. Late Cenozoic uplift has truncated the easterly drainage pattern, exhuming and faulting groundwater-bearing calcrete deposits in the eastern Ti-Tree Basin.

4.3.6.3. Central Ti-Tree Basin Groundwater Resources

The most abundant groundwater resources in the Ti-Tree Basin occur close to the standing watertable and are locally referred to as “upper supplies”. The main aquifer unit was formed in a fluvial environment; it mostly consists of soft silty sand with mixed calcrete and silcrete cement. Collapse of coarse sand and gravel horizons within the aquifer caused considerable drilling problems and made stratigraphic correlations difficult across the basin. The saturated thickness of the upper fluvial aquifer has several compositionally different zones with varying degrees of permeability, namely:

- Silty sandstone is the most abundant sediment type by volume; most silty sandstone units are moderately to highly porous (intergranular and tubular) but have relatively low permeability. Bore yields are commonly >430 m^3-per-day.
- Sand and gravel horizons – these are discontinuous throughout the aquifer and vary spatially and with depth. Most such horizons are highly permeable.
- Calcrete and chalcedony zones are most common in the east of the basin. These form continuous, highly permeable water-bearing zones which have the greatest bore yields, but typically with poorer quality water. Many calcrete deposits are cavernous.

The gradational contact with the lower lacustrine mud effectively forms the aquifer boundary as only small amounts of accessible groundwater occur in the basal unit, e.g., in minor sand-rich horizons. Where the lacustrine mud is absent, the contact with deeply weathered basement marks the lower aquifer boundary. The saturated thickness of the fluvial aquifer in the central basin varies from 70 metres in the west to 30–40 metres further east. The aquifer is effectively unconfined as no confining layer exists. Additionally McDonald (1988) noted that the coincidence of the potentiometric and phreatic surfaces, and the increasing airlift yield of groundwater with increasing depth, provide further support for unconfined aquifer conditions. However, high production zones within the aquifer are semi-unconfined, as indicated by the delayed response at the phreatic watertable after pumping from deeper permeable zones. The average aquifer parameters, as determined from pump testing, indicate that the chalcedonic calcrete zones are the most transmissive parts of the aquifer, with mean transmissivity values of 1,000–1,700 m^2-per-day compared to 160–350 m^2-per-day for the main fluvial sand aquifer. The storage coefficient for chalcedonic calcrete aquifers is also very high (0.38) due to abundant solution cavities. This contrasts to storage coefficient values of 10^{-4} to10^{-3} in the main fluvial sand aquifer, which represents elastic storage plus some contribution from the overlying and less permeable horizons.

The potentiometric surface in the central basin, reconstructed from a relatively large number of bores, indicates a low gradient that falls to the north-east (Figure 4.11). There is a broad subdued recharge mound associated with Allungra Creek, and a north-trending channel sink coincident with the chalcedonic calcrete aquifer. There is also an increase in groundwater elevation levels east of that trough towards the basin margin. Changing water levels between August 1986 and May 1988 indicated rises of up to 0.2 metres in areas of the higher salinity groundwater; falls of up to 1.2 metres occurred in the central basin borefield and the eastern portion of the basin (where abstraction is minimal). Both areas of falling watertable coincide with elevated potentiometric head. The declining head level in the east was probably caused by decay of a recharge mound emplaced prior to monitoring.

The good quality groundwater in the central Ti-Tree Basin (mean TDS <1,000 mg/L) is acceptable for most horticultural enterprises. Nitrate levels are high (70–90 mg/L) to very high (rarely >200 mg/L), and boron levels of 0.65–0.85 mg/L exceed recommended guidelines (0.3 mg/L) for some crops such as grapes. Radionuclide contents (7–10 milliBecquerels-per-litre or mBq/L) are well below potable supply guidelines (100 mBq/L) and pH is near neutral. Harrington et al. (1999, 2002) examined the composition of groundwater in the central Ti-Tree Basin using isotopic and major element analyses. Low salinity (<1,000 mg/L TDS) groundwater of dominantly sodium-bicarbonate-chlorine composition underlies flood-out recharge areas with higher salinity (<4,200 mg/L TDS) sodium-chlorine-bearing groundwater beneath adjacent flat mulga and spinifex plains. Potassium and silica concentrations are relatively high. The ionic species which occur in groundwater with salinities <1,000 mg/L TDS are mostly derived from the weathering of carbonate and silicate minerals and from gypsum dissolution. Higher salinity groundwater is mostly due to the effects of evapotranspiration, cation exchange and carbonate precipitation. Nitrate levels range from 3–380 mg/L (mean = 72 mg/L) with no clear spatial distribution pattern. Nitrogen isotope values ($\delta^{15}N$ of NO_3) range from +2–15‰ and are consistent with termite mound origin and some contribution from mulga decay. Variations in $\delta^{15}N$ are not consistent with de-nitrification of groundwater in the aquifer. High $\delta^{15}N$ is due to loss of ^{15}N-depleted ammonia during the transformation of organic nitrogen into nitrate by termite activity and oxidation. Harrington et al. (1999) concluded that the sodium-bicarbonate-chlorine groundwater has evolved over hundreds to thousands of years by a combination of evapotranspiration, dissolution of carbonate and sulfate minerals and slow weathering of silicate minerals in the soil and saturated zones.

McDonald (1988) reported very low tritium isotope values from groundwater samples just below the watertable, and interpreted these to indicate that direct recharge of the groundwater system had not occurred for more than 25 years (and probably for more than 50 years). Direct recharge is either negligible or occurs at very slow infiltration rates, which leads to tritium depletion. Deuterium depletion (relative to deuterium in rainfall at Alice Springs) provides further confirmation that recharge occurs only from high-magnitude rainfall events. The radiocarbon age of groundwater samples, collected as composites from different aquifer levels, varies from modern to 8,900 years old. Harrington et al. (1999, 2002) provided a more complete comparison of the stable hydrogen and oxygen isotopic signatures of Ti-Tree Basin groundwater and Alice Springs rainwater (Figure 4.13). Isotopic plots of δ^2H versus $\delta^{18}O$ for groundwater samples shows that the trendline of Ti-Tree basin groundwater plots to the right of the Alice Springs rainfall trend. The slope of the trendline is four, which is typical of water which has undergone evaporation during the recharge process. Alice Springs rainfall plots with a slope of about seven, and heavier rainfall is increasingly depleted in heavy isotopes (Figure 4.13). This is consistent with an *amount effect* whereby preferential rainout of heavy isotopes occurs at the beginning of rainfall events. The best-fit line through the groundwater data intersects Alice Springs rainfall at -71‰ for δ^2H and at -11‰ for $\delta^{18}O$ – these values are much lower than the mean annual rainfall composition of -33‰ (δ^2H) and -6.8 ‰ ($\delta^{18}O$). Harrington et al. (1999) concluded that groundwater recharge only occurs following high-magnitude rainfall events (>100 millimetres-per-month) and that evaporation occurs prior to recharge. Later work by Harrington et al. (2002) further restricted the occurrence of recharge to rainfall events

>150–200 millimetres-per-month. Such rainfall events are highly episodic in the Ti-Tree Basin and have only occurred twice in the past 50 years.

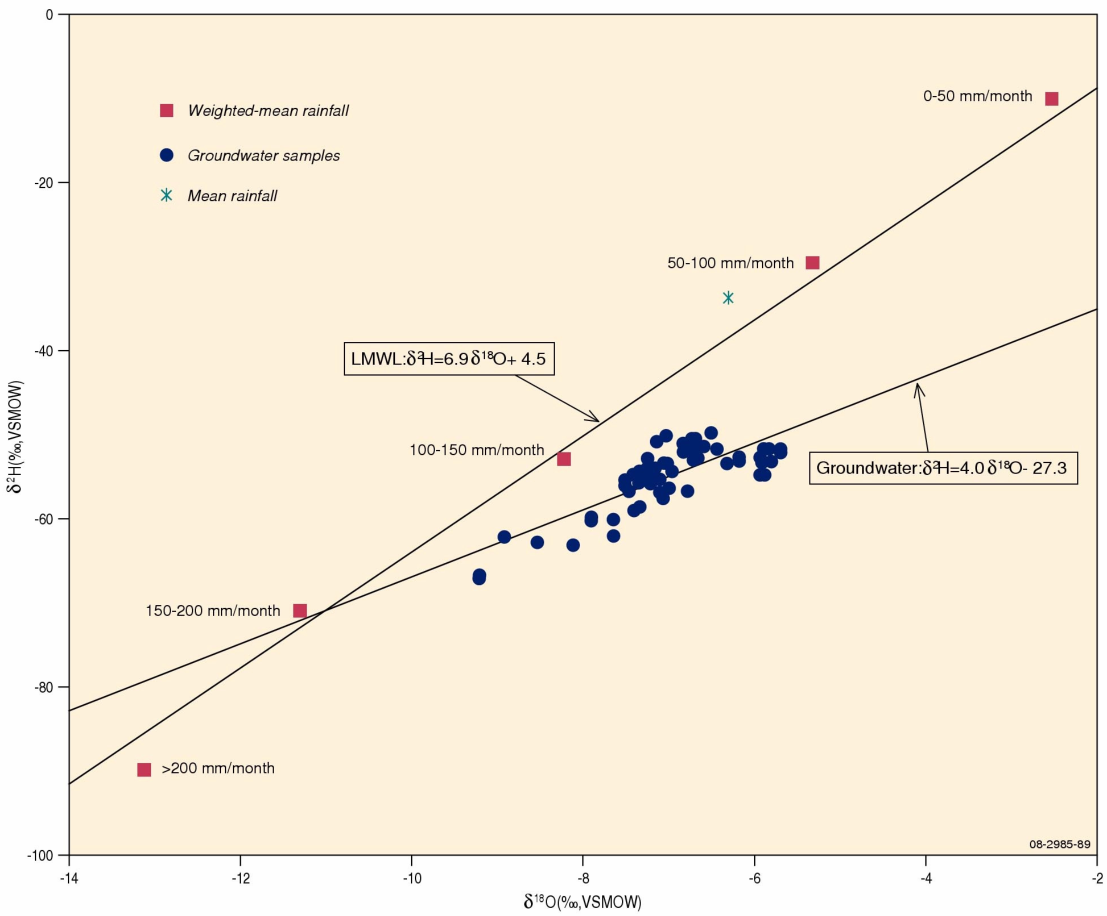


Figure 4.13: *Plot of δ^2H versus $\delta^{18}O$ for groundwater samples from the Ti-Tree Basin and rainfall from Alice Springs. The significantly different trendline for the groundwater data compared to local rainfall shows that groundwater has been affected by evapotranspiration processes during recharge. Figure is modified from Harrington et al. (1999).*

The declining watertable in central Ti-Tree Basin demonstrates that current recharge rates are below discharge rates, due to evapotranspiration in the north of the basin or by outflow to the north-eastern palaeovalley outlet. Recharge rates are also less than in the past when significant recharge events must have occurred. McDonald (1988) considered that direct recharge was minimal despite the lack of runoff on sandy soils within the basin. As evidence, McDonald highlighted that 250 millimetres of rainfall in March 1983 had resulted in infiltration to depths of only two metres after two weeks, and concluded that most rainfall is probably lost by evapotranspiration. Additionally, with relatively uniform landscapes and soils across the basin, direct recharge cannot explain the presence of discrete recharge mounds with low salinity and low chloride groundwater. The depleted tritium values in the Ti-Tree groundwater indicate that direct recharge is extremely slow or negligible. Therefore indirect recharge from runoff is likely to be the dominant recharge mechanism.

The Allungra Creek catchment comprises 375 square kilometres of mostly bare basement rocks. This drainage collects runoff that flows east then north where it floods-out onto the sandy surface of the basin, diverging to multiple distributary channels including one that extends at least 25 kilometres to the northern edge of the basin. Minor floods onto the basin are restricted to the distributary drainage network and infiltration to groundwater is probably minimal. Most water is likely discharged by evapotranspiration from deep-rooted trees that line the channels, resulting in minor amounts of relatively high-salinity recharge water close to the channels. Floods from rare high-magnitude rainfall events are not confined to the distributary channels and may flood-out broadly across the basin sand plain to the north until impeded by dunes. This results in widespread infiltration and recharge of lower salinity water which is not significantly impacted by evapotranspiration because shallow-rooted non-tree vegetation is predominant away from the channels. McDonald (1988) reported that the flood-out process was clearly evident in Landsat imagery following extremely high magnitude rainfall in January 1974. Aileron, the closest rainfall station, received 589 millimetres of rain between November 1973 and February 13, 1974 (the date of the Landsat image), including 405 millimetres in January. Substantial floods occurred in the Hanson River and Woodforde River and in Allungra Creek during this event. Enhanced recharge from such events is consistent with the low-chloride and low-salinity recharge mound in the potentiometric surface, which likely takes many years to decay between recharge events. NRETA (2007) reported that the watertable had not fallen to pre-1970 levels following significant recharge in the wet years of the mid- to late-1970's. However, the watertable rose several metres in the western part of the basin following the 1974 floods in the Hanson and Woodforde rivers. McDonald (1988) concluded that insufficient records existed for long-term rainfall, runoff extent and waterbore monitoring to quantify the required magnitude or return period of high-magnitude rainfall events which have resulted in significant recharge.

Harrington et al. (1999; 2002) used chloride concentrations and radiocarbon data to quantify recharge in the Ti-Tree Basin. Groundwater chloride concentrations range from 70–1,270 mg/L; low chloride levels occur near Allungra Creek (central) and Woodforde River (west) flood-outs. Chloride in the basin is mainly derived from rainfall and dry fallout as basement rocks are chloride-poor. Alice Springs rainfall contains 0.5 mg/L of chloride and mass balance calculations indicate recharge of 0.1–2 millimetres-per-year, with the highest recharge rates in the low-chloride flood-out areas. Radiocarbon ages indicate that groundwater varies from modern to about 20,000 years old, and is mostly <8,000 years although there are no consistent depth or hydraulic gradient trends. Harrington et al. (1999) corrected for the addition of old carbon from the dissolution of carbonates or the oxidation of old organic matter by a specific scheme applicable to arid zone sandstone and carbonate aquifers. This method partitioned the relative contribution of ^{14}C and ^{12}C to groundwater from soil CO_2, carbonate and silicate weathering processes by a combination of chemical and strontium isotope mass balance calculations. Combining groundwater ages and the depth below watertable, Vogel (1967) developed a method to estimate recharge rates over the interval between where the groundwater sample entered the saturated zone and the bore location. The chloride mass balance method provides an estimate of recharge where the sample first enters the saturated zone. The 3.5 millimetre-per-year mean recharge rate that Harrington et al. (1999) determined from ^{14}C is significantly higher than the 0.8 millimetre-per-year rate derived from chloride mass balance calculations (although the higher rate is significantly biased by groundwater samples from two bores which have extremely high ^{14}C recharge values of 27 and 50 millimetres-per-year). The highest ^{14}C-determined recharge rate of 8.8 millimetres-per-year comes from the central basin in the Allungra Creek flood-out but is also biased by the two anomalous values (referred to above). High ^{14}C-determined recharge also occurs in western areas near the Woodforde River. Harrington et al. (1999) concluded that the long-term mean annual recharge rate for groundwater with salinity levels <1,000 mg/L TDS is 1.9 millimetres-per-year. This equates to a volume of 1.14 x 10^6 m^3. Recharge rates for the remainder of the Ti-Tree Basin average 0.2 millimetres-per-year, which suggests that the total volumetric recharge across the entire basin is 2.12 x 10^6 m^3.

The rate of throughflow of low salinity groundwater (<1,000 mg/L TDS) in the Ti-Tree Basin has been estimated at 3,120 m^3-per-day, based on transmissivity data from pump testing and from the groundwater gradient and width of the flow path measured from drilling. Ride (1968) provided the first estimate of specific yield (0.03) from the western basin, although this was subsequently refined from borefield production data in the central basin to 0.06 (McDonald, 1988). The natural 0.2 metre decline in water-level is associated with throughflow and, using a conservative specific yield of 0.05, indicates an aquifer dewatering volume of 6.24×10^4 m^3-per-day or 2.28×10^7 m^3-per-year. These values correspond closely with the volume of water estimated by a 0.2 metre fall in potentiometric head (McDonald, 1988). Thus, throughflow in the central Ti-Tree Basin is presently due to head decay rather than recharge, and the potentiometric surface is unstable.

In the central basin, the freshest groundwater resource (<1,000 mg/L TDS) occurs over 600 square kilometres or 10% of the total basin area. At an average saturated aquifer thickness of 55 metres the total aquifer storage volume is about 3.3×10^6 m^3 (McDonald, 1988). Using a conservative specific yield of 0.05 indicates that the theoretically extractable volume of fresh groundwater from the central basin is 1.65×10^9 m^3. The ratio of throughflow to extractable storage in the central Ti-Tree Basin is thus 1:1,450. Elsewhere in the basin the rate of throughflow is likely to be lower compared to storage as gradients are lower. The median recharge rate for the central basin is about 1.9 millimetres-per-year, hence the annual volume of recharge for the 600 kilometre^2 zone of fresh groundwater is 1.1×10^6 m^3 (Harrington et al., 1999). Using the total volume of groundwater in the basin estimated by McDonald (1988) (3.3×10^{10} m^3) the average groundwater turnover time is 2,900, i.e., the total storage divided by the recharge flux. This equals the time required to replenish a totally depleted storage.

Three regions of the Ti-Tree Basin have groundwater resources which are sufficient for irrigated horticulture operations; the western (Woodforde), central and eastern (Atartinga) zones. McDonald concluded that each can be exploited separately without adversely affecting other zones, but that abstraction of these resources will effectively result in mining the groundwater system because of infrequent recharge events. From the upper limit provided by the extractable volume of 1.65×10^9 m^3 in the central basin, extraction of 1% per year would equal 1.65×10^7 m^3, which could potentially irrigate 600 hectares with 2.5 metres of water. Abstraction at this rate would greatly exceed basin throughflow and result in local drawdown and reversal of potentiometric gradients. Optimal resource management would require regulation and monitoring of abstraction. Harrington et al. (1999) concluded that sustained groundwater use of more than 0.03% of the resource per year would have long-term adverse impacts on the groundwater system. Other effects such as lateral flow of more saline groundwater, induced by drawdown, could also affect horticultural activities before groundwater storages were fully depleted. Additionally, high nitrate levels over most of the basin would require treatment for potable water supplies used for nitrate-sensitive crops.

4.3.6.4 Ti-Tree Basin Groundwater Abstraction

Over the past decade groundwater-irrigated horticulture has expanded in the Ti-Tree Basin and a number of studies have focussed on achieving a sustainable management regime. The existing Northern Territory management policy (DIPE, 2002) permits maximum groundwater extraction of 10.22×10^6 m^3-per-year. This includes 3.2×10^6 m^3-per-year from the western zone, believed to be sustainable (lower than recharge), 7.0×10^6 m^3-per-year from the central zone, which exceeds recharge but at an acceptable level of long-term storage loss (>200 years), and minimal (0.2×10^6 m^3-per-year) from the eastern zone where the irrigation potential is yet to be quantified. The management strategy (DIPE, 2002) also included a detailed list of investigations, reviews and ongoing monitoring to improve knowledge and information about the basin and its response to abstraction and to inform future management strategies. Knapton (2006) reviewed the overall condition of the basin and its response to groundwater abstraction for the year 2005–2006 and concluded that there were minor declines in the regional watertable and more significant declines in the local watertable around the main borefields. The borefield declines exceeded predictions from the water balance modelling used for management, indicating that current water allocation at the Ti-Tree Farms borefield can only be maintained for 20–30 years, much lower than the original model predictions. Knapton (2006) suggested three possible explanations for this discrepancy: 1. the modelled transmissivity or storage values are greater than the actual values; 2. the modelled groundwater recession is lower than the actual level; and 3. abstraction rates are higher than reported. As divergence from the modelled response is limited to the borefields rather than the entire basin, Knapton (2006) favoured higher than actual modelled transmissivity values or higher than reported abstraction rates as the most likely explanation. Knapton (2006) also indicated that groundwater quality has remained virtually unchanged during this time and is unlikely to deteriorate in the next 5–10 years, though he conceded that this conclusion was based on minimal data.

The conceptual model of the hydrology of the basin (Water Studies, 2001) assumed a two-layered aquifer system with a low permeability upper-layer and a high-permeability and high-yielding lower layer. Aquifer transmissivity, as derived from pump testing, varies from 180–500 m^2-per-day with an assumed average of 270 m^2-per-day. Estimates of the specific yield vary from 0.03 to 0.1; an average of 0.07 provides for storage volume of 8.65 x 10^9 m^3 across the 4,700 $kilometre^2$ aquifer area with an average saturated thickness of 26.3 metres. Recharge occurs from direct infiltration through soils and from surface depressions that collect rainfall (3.62 x 10^6 m^3-per-year) and from infiltration from stream-flow flood-outs (6.42 x 10^6 m^3-per-year). This gives a combined total recharge volume of 10.04 x 10^6 m^3-per-year which was assumed to be balanced by evapotranspiration and outflow to the north (DIPE, 2002). The recharge estimate is derived from a simple catchment model which is calibrated by recharge values determined from watertable monitoring of bores in the Ti-Tree Farms borefield from 1967 to 1975. This period included the anomalously wet years of 1973–1974 with provided an unprecedented volume of recharge from which the basin watertable is still declining. The total basin recharge of 10.04 x 10^6 m^3-per-year used for management modelling is about five-times the long-term mean annual recharge rate for the total basin (2.12 x 10^6 m^3-per-year), as derived from chloride, isotope and radiocarbon tracer studies by Harrington et al. (1999; 2002). More significantly, the management modelling recharge estimate is a tenfold increase over the 1.14 x 10^6 m^3-per-year of fresh (<1,000 mg/L TDS) groundwater recharge which was estimated by Harrington et al. (1999; 2002).

4.3.7. The Willowra Palaeovalley

Morton (1965) reported the results of a detailed stratigraphic and groundwater drilling investigation on Willowra Station north-west of Alice Springs. This study investigated the potential for irrigated horticulture to be developed in the area following drilling of a pastoral station bore which produced a high flow of potable water (~1,000 mg/L TDS). The stratigraphic sequence containing the aquifer was named Willowra Basin by Morton but was clearly identified as fluvial infill of a Cenozoic drainage system and is here referred to as the Willowra Palaeovalley.

The Willowra Palaeovalley is situated north-west of the Ti-Tree Basin, at the junction of the Lander River and Ingallana Creek (Figure 4.14). The landscape of the region is dominated by spinifex-covered sand plains and hills of basement rocks which rise up to 70 metres above the plain. The climate is arid with about 300 millimetres of summer-dominant rainfall and little runoff except from outcropping bedrock hills. The regional geological terrane comprises of deeply weathered (up to 60 metres deep) and ferricrete-covered Archaean metamorphic and granitic rocks overlain by Proterozoic sandstone, shale and quartzite.

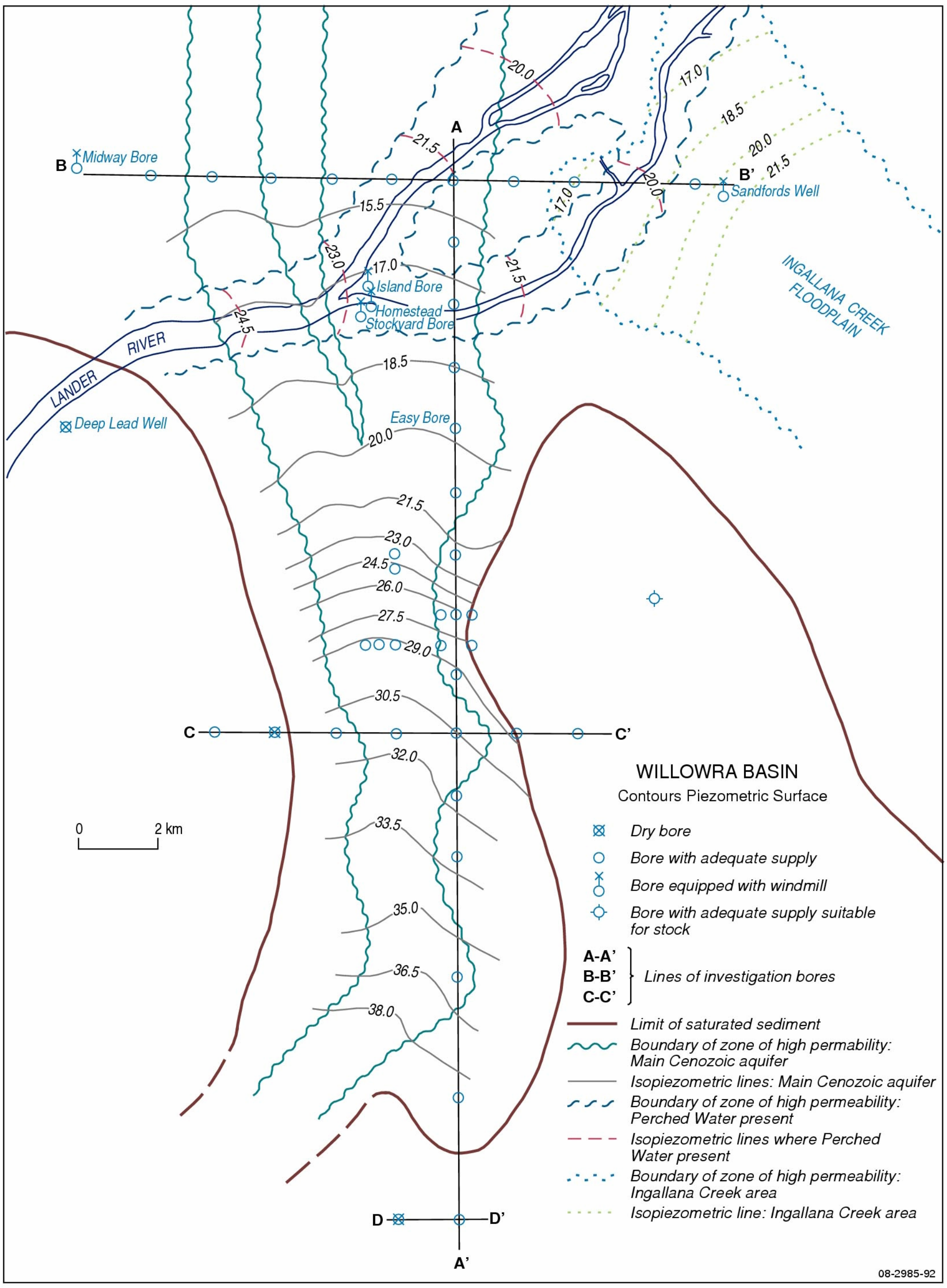


Figure 4.14: Potentiometric groundwater surface map of the Willowra Palaeovalley in central Australia, showing that groundwater flow is north-directed. The location of previous detailed investigation drilling transects across the palaeovalley are also shown. Figure is modified from Morton (1965).

The deep weathering profile on the basement rocks consists of three horizons, typical of north Australian ferricrete profiles and described by Morton (1965), in descending order, as:

- **Ferruginous zone:** 3–20 metres of red, earthy massive or pisolitic haematite-bearing ironstone.
- **Mottled zone:** 3–12 metres of earthy material, mottled red and white.

- **Pallid zone:** 6–25 metres, with minor traces of parent rock material, white earth and kaolinite with quartz, mica and feldspar increasing downwards to a parent rock transition zone.

Morton also described secondary chalcedonic silcrete on quartzite outcrops. The deeply weathered and ferricrete-covered basement rocks are incised by palaeovalleys to about 30 metres, and these groundwater systems were the target of the previous stratigraphic and groundwater investigations.

Investigation of the Willowra Palaeovalley included drilling by the Northern Territory Water Resources section, with 29 holes drilled between February and July 1963 (698 metres total drilling), and a further 16 holes drilled in October 1963 (726 metres in total). The holes were sited on a 1,524 metre grid which was referenced relative to the previously successful station bore. Three of the initial 29 rotary holes drilled into deeply weathered basement outside the palaeovalley, 11 holes penetrated the palaeovalley sediments down to underlying weathered basement rocks and 15 holes failed to penetrate to the deeply weathered basement due to the presence of unconsolidated sands which caused holes to collapse. All 16 later holes penetrated through the palaeovalley infill sequence and four holes ended in fresher bedrock. Aquifer pump tests were not undertaken but air-lifting to clean out the drillholes indicated large groundwater supplies in palaeochannel sands and the deeply weathered basement rocks.

Drilling showed that the palaeovalley infill sediments are mostly brown clay and silt deposits with elongate sand and gravel lenses running parallel with the north-trending palaeovalley (Figure 4.15). About 25 kilometres south of Willowra Homestead the palaeovalley is about 18 metres-deep and 3 kilometres-wide, deepening to 35 metres just north of the homestead. The shape and sediment composition of the infill sequence indicates that it formed in a fluvial environment, with elongate sand and gravel channel lenses and clay and silty-clay sediments typical of floodplain overbank deposits. Morton (1965) considered that the fluvial sediments were locally derived from the deeply weathered basement rocks, with much of quartz reworked from the pallid zone of the weathering horizon. Two distinct periods of channel sand deposition are separated by clay and silt horizons, interpreted by Morton (1965) as indicating a quiescent interlude between more active fluvial episodes. The top of the lower channel sand typically lies about 17 metres below ground surface and the base of the upper channel at about nine metres. Morton (1965) assigned an Upper Tertiary age to these sediments by correlation to Alcoota where Pliocene vertebrate remains occur in sediments with a similar stratigraphic setting. It is not clear how the fluvial section relates to other palaeovalley or Cenozoic basin sequences from central Australia or in other arid zone regions. Morton (1965) made no reference to carbonaceous facies or lignite which might have potential for retrospective palynological dating.

Morton (1965) also reported post-palaeovalley deposits at Willowra. Calcrete occurs in two forms separated by a vertical gradient:

- Uppermost are large concretionary masses termed **kunkar**; these have a likely pedogenic origin derived from meteoric water; and
- Deeper deposits cement the palaeovalley sands and have a groundwater origin; these are termed **calcrete**.

Secondary iron commonly cements the margins of channel sands and is interpreted as remobilised iron from fluvial reworked ferricrete. Some calcrete occurs below ferricrete separated by thin sand or silt. Quaternary to recent incised channels of the Lander River and Ingallana Creek may cross or coincide with the palaeovalley, and these contain 6–15 metres of sand and gravel.

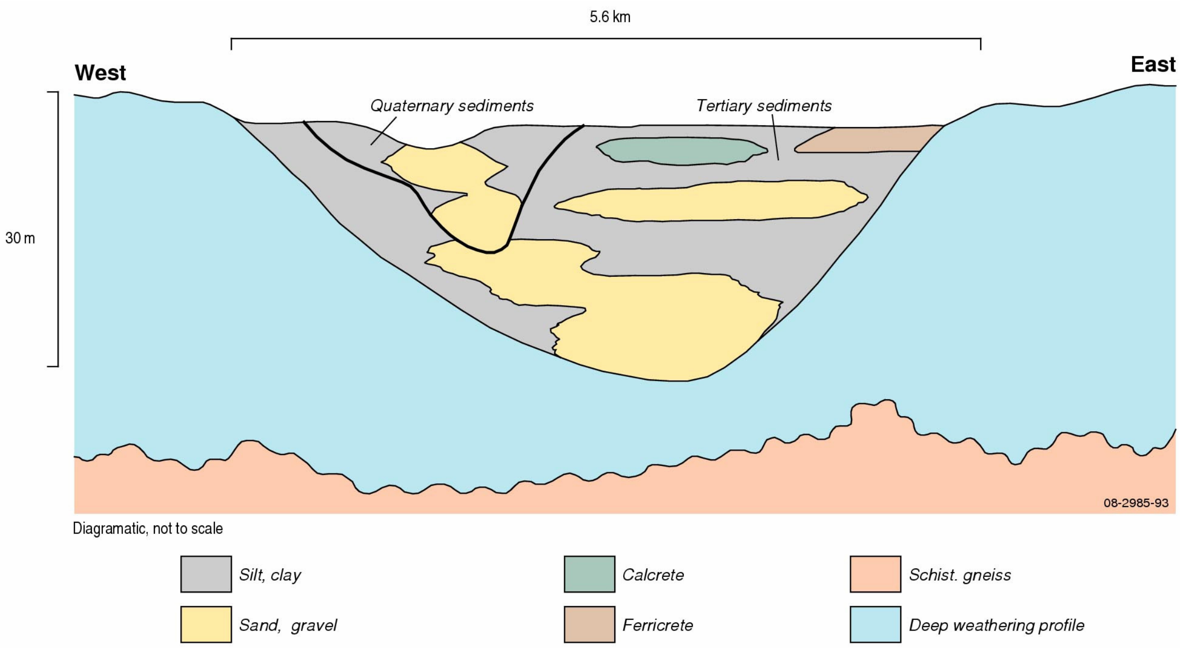


Figure 4.15: *Diagrammatic cross-section through the northern part of the Willowra Palaeovalley showing the typical distribution of the main channel-fill facies above deeply weathered bedrock. Figure is modified after Morton (1965).*

4.3.7.1. Willowra Palaeovalley Groundwater

Groundwater resources at Willowra occur in deeply weathered basement rocks, palaeovalley sand deposits and the modern alluvial sediments, probably with some degree of interconnection. The deeply weathered basement is saturated below the watertable, and minor volumes of groundwater are stored in original vuggy or secondary solution porosity in ferricrete and mottled zones. More abundant groundwater occurs in uncemented pallid zone and saprolite horizons rich in quartz (a legacy of quartz-bearing gneissic parent rocks) but not in kaolinite-rich zones (derived from mica-schist parent rocks). Water quality in the deeply weathered basement varies according to the recharge source.

In the palaeovalley infill sequence the lower channel sand is the main aquifer system and is confined by silty-clay floodplain deposits. The upper channel sand above the aquiclude is commonly above the watertable. The lower palaeochannel sand aquifer consists of clean, medium- to very coarse-grained sand and gravel; the sequence becomes thicker (increasing from 6 metres to 17 metres) and contains less abundant clay downstream. The sand aquifer is lenticular in cross-section and has a maximum width of about 1,600 metres with an estimated total storage volume of 4.93 x 10^8 m^3 within the original investigation area (Figure 4.15). The Quaternary alluvial aquifer is not separated from the palaeovalley sediments by an aquiclude and thus loses water after streamflow to the underlying palaeovalley aquifers. The Quaternary alluvial aquifers have low volumes of groundwater storage after long periods of low flow. Morton (1965) reported that the watertable depth in the Willowra Homestead bore, which penetrates 15 metres of Quaternary fluvial sands, varies from about 12 metres (in dry periods) to near-surface immediately after streamflow.

Groundwater flows northward along the palaeovalley and under the Lander River, especially in high-permeability zones of the palaeochannel sand aquifer. Local recharge of higher salinity water occurs from the deeply weathered basement aquifers. Groundwater flows at shallow depth in the

Quaternary alluvial aquifer of Ingallana Creek but cannot flow up-gradient into the palaeovalley aquifer. The Quaternary alluvial Lander River aquifer contains perched low-salinity groundwater and the watertable level fluctuates widely (according to river flow); it also provides minor recharge to the underlying sand aquifer. However, the main area of recharge to the palaeochannel aquifer occurs in the southern (upstream) part of the palaeovalley where Quaternary sands of Lander River connect with the palaeovalley sediments. Groundwater salinity contours indicate that recharge of higher salinity water occurs from weathered and unweathered basement rocks east of the palaeovalley. Groundwater throughflow under the palaeovalley may occur in permeable deeply weathered basement rocks, recharged by runoff where exposed at surface. Recharge of the permeable (quartz-rich) pallid zone can occur where it contacts the palaeochannel sand aquifer – this occurs only in a narrow zone where suitable parent rocks exist. The shallow palaeovalley sands under Ingallana Creek are recharged from the Quaternary channel aquifer and the adjacent deeply weathered basement.

Groundwater salinity levels are variable and mostly <3,600 mg/L TDS in the palaeovalley and Quaternary alluvial aquifers, although salinities up to 17,000 mg/L occur in deeply weathered basement aquifers. Morton (1965) recognised three groundwater types based on composition:

- Groundwater with relatively high TDS (750–9,900 mg/L), which occurs in basement rocks, deeply weathered basement aquifers and kunkar calcrete aquifers. Carbonate plus bicarbonate forms <50% total anions, which exceed calcium plus magnesium levels which are <50% of total cations. Chloride and sodium levels are high, sulfate is commonly high and hardness is medium to low.
- Groundwater with relatively low TDS (<1,124 mg/L), which occurs in Quaternary alluvial and palaeovalley aquifers and has calcium plus magnesium levels >49% of total cations, exceeding carbonate plus bicarbonate contents which have highly variable abundances. These alkali-carbonate waters contain abundant bicarbonate and sodium and low levels of chloride. This groundwater type also occurs in deeply weathered basement rocks where recharge from palaeochannel sand aquifers occurs.
- Groundwater with moderate salinity (TDS of 750–1,500 mg/L) and mixed characteristics of the other classes occurs where palaeovalley aquifers are influenced by recharge from deeply weathered basement aquifers. Carbonate plus bicarbonate forms <50% of the anions and exceeds calcium plus magnesium levels which comprise <50% cations. Chloride, bicarbonate and sodium are relatively abundant.

By comparison with horticultural areas with similar soils and groundwater characteristics elsewhere in the Northern Territory Morton (1965) concluded that groundwater in the Willowra Palaeovalley is suitable for some horticultural enterprises, e.g., lucerne cropping, which has a relatively high salt tolerance. Additionally, groundwater in some deeply weathered basement aquifers is potentially suitable for growing salt-tolerant crops. However, Morton (1965) regarded groundwater from the Quaternary alluvial aquifer at Ingallana Creek as unsuitable for horticulture.

4.4. TANAMI

The Tanami region has a hot semi-arid climate dominated by summer rainfall and with high annual evaporation rates, e.g., at the community of Rabbit Flat average annual rainfall is 450 millimetres and average pan evaporation is 3,750 millimetres. Palaeovalleys in the Tanami were studied in some detail as part of a hydrogeological assessment by Domahidy (1990) and also for wider regolith mapping of the Granites–Tanami region by Wilford (2000). Information in this section is mainly derived from those sources.

Relief in the Tanami region is low, ranging from about 330 metres AHD to 500 metres AHD at Mt Tanami, and the landscape consists mainly of low-lying weathered bedrock outcrops in a sandplain with some areas of west-north-west oriented longitudinal dunes. The region includes parts of two major tectonic units – the early Proterozoic Granites–Tanami Block which is separated unconformably from Mid to Late Proterozoic clastic sedimentary rocks of the Birrindudu Basin. The Tanami–Granites Block comprises of unaltered but variably metamorphosed sedimentary, volcanic and granitic rocks which are steeply dipping and tightly folded. Early Cambrian basalts (Antrim Plateau Volcanics) unconformably overlie the older rocks in the Tanami region. These were formed by sub-aerial or shallow marine lava flows across broad shallow valleys, and are commonly intercalated with shallow marine sedimentary rocks. To the north-east of the Tanami, flat-lying Middle Cambrian marine and shallow marine sedimentary rocks overlie the Granites–Tanami complex. Palaeovalleys with deeply weathered bedrock and some silicified alluvial sediments are preserved in some areas beneath the Antrim Plateau Volcanics (Figure 4.16).

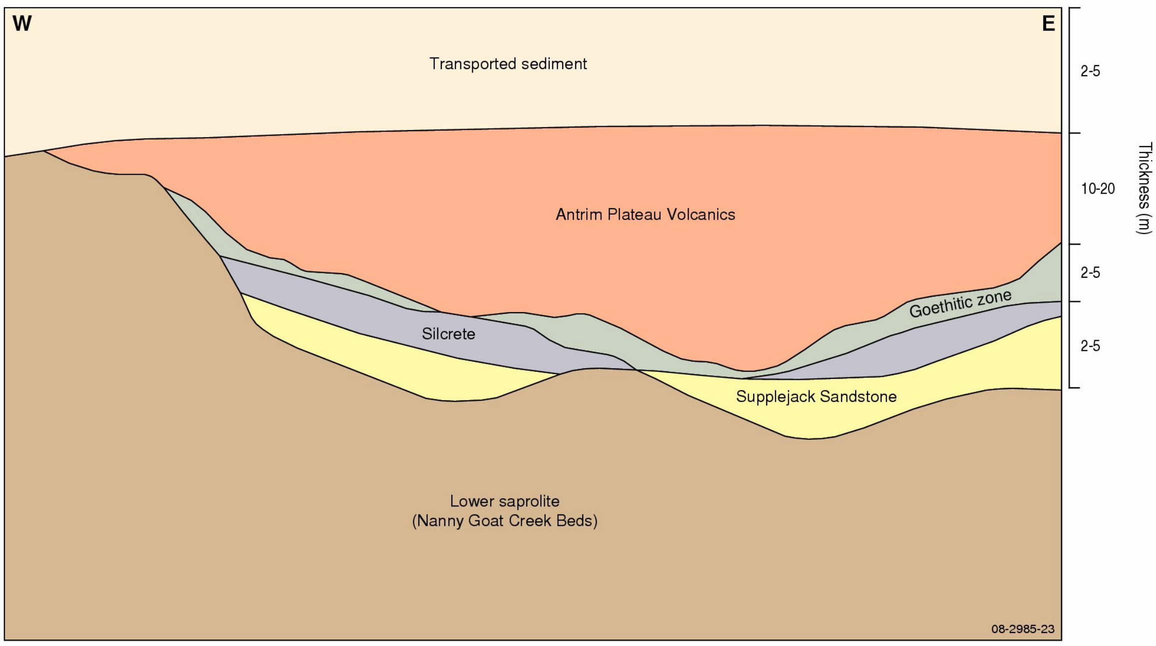


Figure 4.16: *Schematic cross-section showing typical stratigraphic sequence developed for Palaeozoic palaeovalleys in the Tanami region which are preserved beneath the Cambrian Antrim Plateau Volcanics. This section is based on drilling near Supplejack and shows the preserved valley profile developed in weathered (saprolitic) bedrock and infilled with partly silicified alluvial sediments (here termed the Supplejack Sandstone).*

Ferricrete-capped deep weathering profiles are also developed on most Proterozoic to Mesozoic rocks. Cenozoic surficial deposits of aeolian sand, alluvial sand/silt/clay, gravel, calcrete, silcrete and minor evaporite are widespread and form relatively thick sequences in the Cenozoic-filled palaeodrainage network, which is much more widespread than the Cambrian palaeovalleys (Wilford, 2000). Domahidy (1990) identified two large palaeovalleys in the region, one west-trending and the other south-trending, which converge between Rabbit Flat and Tanami Downs and then head southwards towards Lake MacKay, incorporating additional tributaries on the way. Detailed mapping by Wilford (2000) identified and delineated a more extensive and higher-order palaeodrainage network using surface flow modelling, which derived surface flow vectors using various attributes from a digital elevation model such as flow direction and slope and flow accumulation signals. The detailed palaeodrainage network defined by Wilford (2000) was further supported by radiometric imagery, based mainly on the moderate to high potassium gamma-ray signature associated with alluvial clays.

The Cenozoic palaeodrainage system in the Tanami forms a network of topographic depressions with broad trunk palaeovalleys and narrow higher-order palaeovalleys, with evidence for significant tectonic disruption and diversion (Figure 4.17).

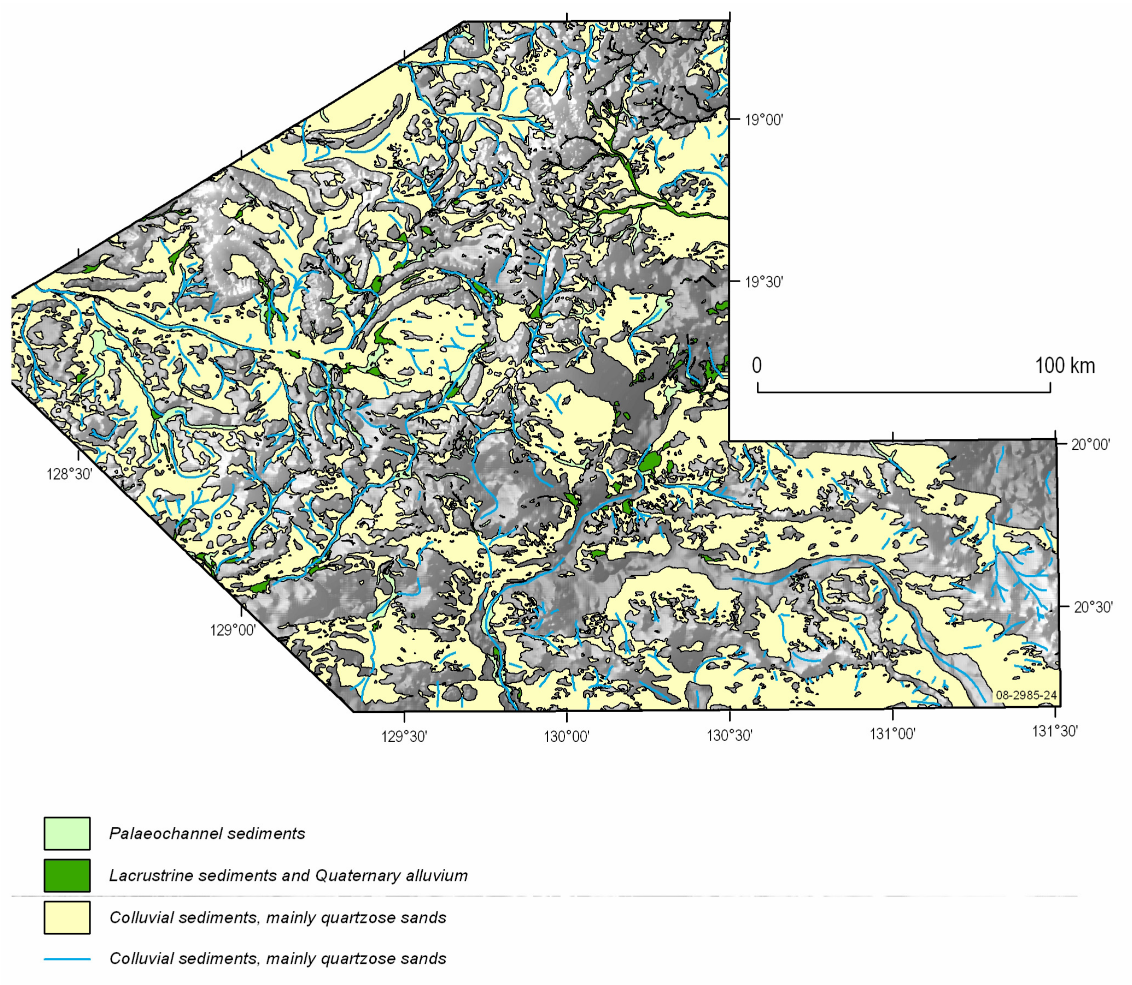


Figure 4.17: *Map of the palaeodrainage system in the Tanami region, showing the distribution of the larger trunk palaeovalleys (marked in green) and the higher-order tributary system (blue drainage lines). Figure is modified from Wilford (2000) (Figure 4.6).*

The known palaeovalley system indicates incision of an extensive perennial river network during previous wetter climates, which formed a pre to Early Cenozoic landscape with considerably greater relief than present (Wilford, 2000). The palaeovalleys are incised into ferricrete-capped and deeply weathered bedrock. Silicification of the palaeovalley sediments and the weathered bedrock is common and may overprint ferricrete (Wilford, 2000). Trunk palaeovalleys contain unconsolidated alluvial clay and silt with common intercalated fine- to coarse-grained sand and gravel and various chemical precipitate deposits such as calcrete and silcrete (Figure 4.18). Their courses are marked by sporadic, mostly round, salt and clay pans, which contain thin crusts of gypsum and other salts.

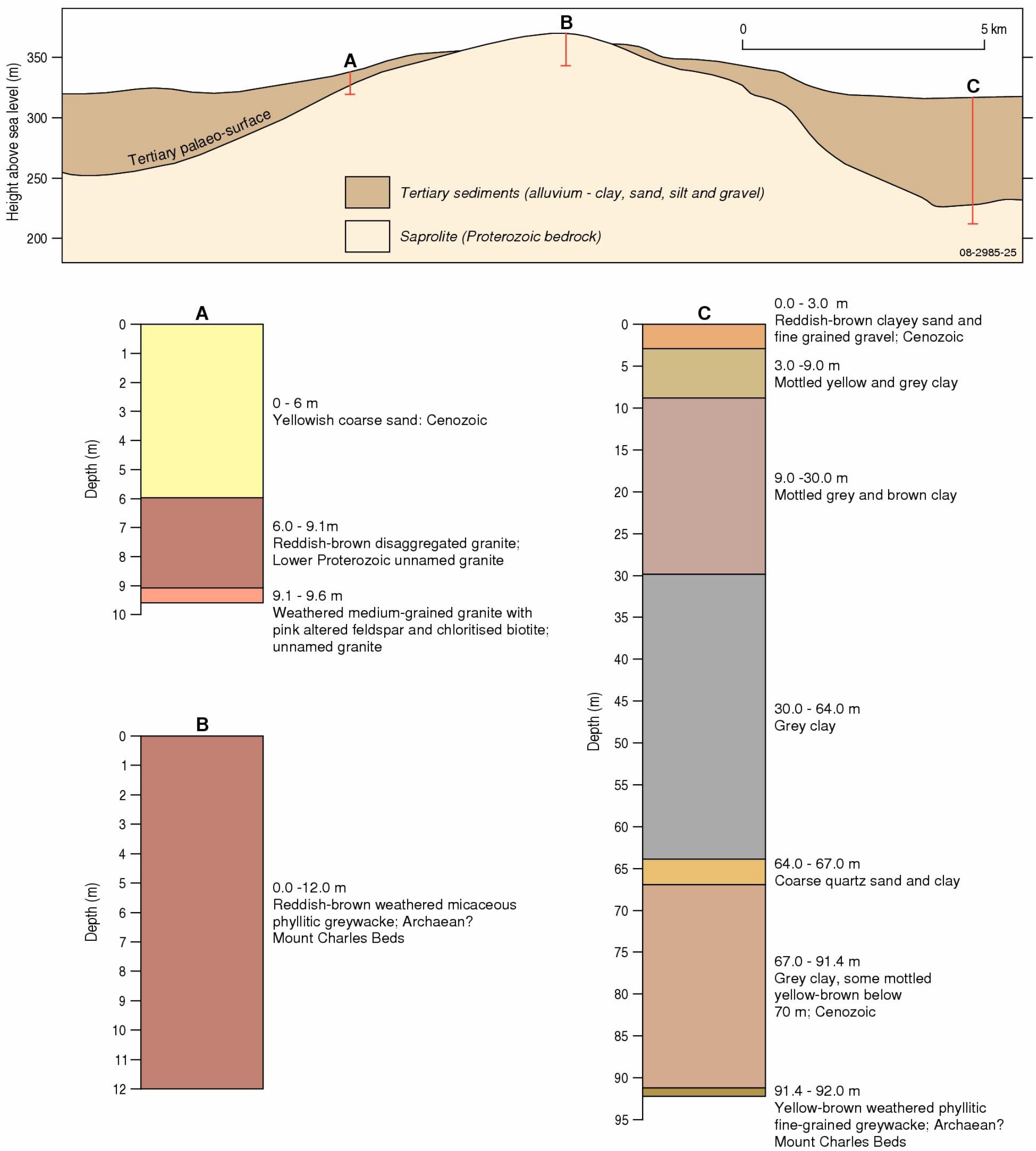


Figure 4.18: *Multiple stratigraphic profiles through Cenozoic palaeovalley deposits and deeply weathered bedrock between the Granites and Tanami gold mines in the Tanami region. These profiles show the typical variation in palaeovalley sediment deposits and weathered bedrock across the region. The stratigraphic columns and cross-section are based on drilling undertaken by the Bureau of mineral Resources in 1974. Figure is modified from Blake (1974).*

Extensive drilling has shown that up to 90 metres of infill sediment has been deposited in trunk palaeovalleys near Tanami Downs Homestead and in the Tanami Mine borefield. The narrower higher-order palaeovalleys consist mostly of alluvial and colluvial material and are covered by sheet-flood fan colluvium with little surface expression of the underlying palaeovalleys (Wilford, 2000). The exact age of the Cenozoic palaeovalley sediments is not known although Wilford (2000) summarised the regolith and landform history of the region and suggested that deep weathering (and presumably channel incision) occurred in the relatively wet climate regime of the Palaeocene and Eocene. This was followed by deposition of palaeovalley infill sediments from the Middle Miocene as the climate gradually became drier. Secondary chemical precipitate and playa lacustrine deposits formed after palaeovalley infill and occlusion of surface flow.

Massive and tabular calcrete is common throughout the region and is preferentially developed near the mid-point of most palaeovalley systems. Calcrete deposits have formed by cementation and accumulation of carbonate principally within the phreatic zone, and by surface sheetwash and subsurface groundwater flow. Carbonate is probably sourced from a combination of wind-blown dust, aerosols dissolved in rainfall, and weathering of calcium- and magnesium-rich bedrock (Wilford, 2000). Precipitation of secondary calcrete, as calcite, displaces primary sediments and results in upward growth of low hummocky outcrops formed of white to pale grey inorganic calcrete, with sand grains and rock fragments common in the secondary cement (Figure 4.19). Mounded calcrete bodies are typically elevated several metres above the surrounding palaeovalley surface. Partial or complete replacement of basal calcrete by silcrete (opaline and chalcedonic silica) is also common (Domahidy, 1990; Wilford, 2000). Although most silica deposits are massive, the development of extensive fissures and cavities creates high permeability zones which are conducive to groundwater storage and transmissivity. The thickness of calcrete deposits averages 12–15 metres (maximum of 18 metres of calcrete at Tanami Downs) and most are underlain and flanked by alluvial clay, sand and gravel. Calcrete also occurs widely in the sub-surface.

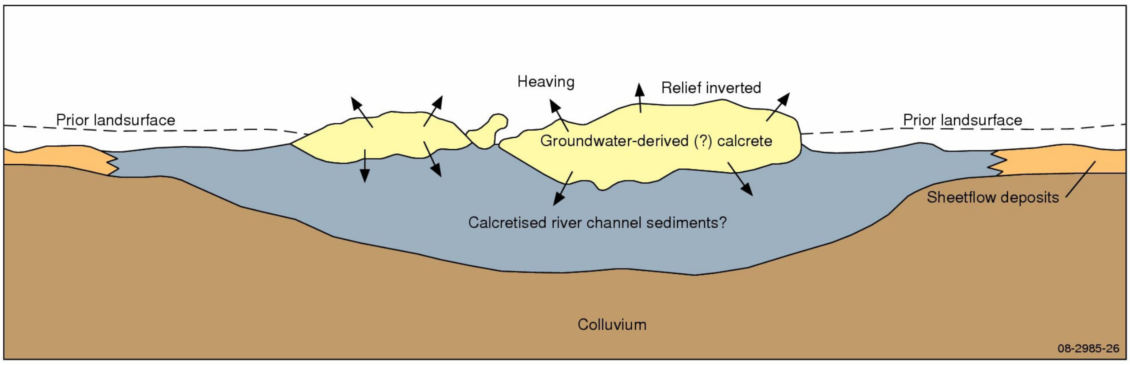


Figure 4.19: *Schematic representation of calcrete mounding in Tanami palaeovalleys. Relief inversion is caused by upward movement as the calcrete deposit grows (expands) during precipitation, and the surrounding sediments are locally eroded. Figure is modified from Wilford (2000) (Figure 8.5).*

4.4.1. Tanami Palaeovalley Groundwater Resources

Minor aquifers in the Tanami region include fractured bedrock and porous zones of unmetamorphosed Middle and Upper Proterozoic sedimentary rocks. However, the major groundwater resource occurs in palaeovalley sediments and chemical deposits. Calcrete is extensive, highly permeable and the most productive aquifer. Silcrete which replaces calcrete is commonly fissured and contains highly permeable cavities. Table 4.3 contains production bore yield data for various aquifers in the Tanami region.

At Dead Bullock Soak, a bore sunk in fractured mafic volcanic rocks (Mount Charles Beds) produces about 85 m^3-per-day. At the Tanami Borefield, two bores in weathered and fractured basalt have a maximum sustainable supply of 130 m^3-per-day, aquifer transmissivity of 20 m^3-per-day-per-metre and a storage coefficient of 1.3 x 10^{-3}. At the Granites, bores in quartz-biotite schists yield <80 m^3-per-day and both the aquifer transmissivity and storage coefficient are low (<5 m^3-per-day-per-metre and about 1 x 10^{-5} respectively). The watertable here occurs at depths of 40–50 metres. The most prospective parts of the Mount Charles Beds are fractured mafic volcanic rocks, banded chert and basalt; many bores, however, have been unsuccessful (Domahidy, 1990). Groundwater obtained from the Mount Charles Beds is either brackish (1,000–5,000 mg/L TDS) or saline (>5,000 mg/L TDS), with high sulfate and low bicarbonate compositions.

Table 4.3: Yields from Tanami production bores (after Domahidy, 1990).

AQUIFER	NUMBER OF BORES	AVERAGE BORE YIELD (m^3/day)	MAXIMUM BORE YIELD (m^3/day)	AVERAGE BORE DEPTH (m)
Palaeovalley alluvium	2	170	430	84
Palaeovalley calcrete	21	170–860	1,730	25
Pedestal Beds (Palaeozoic sandstone)	2	170	170	36
Murial Range Sandstone (Proterozoic sedimentary rocks)	1	105	170	37
Mount Charles Beds (fractured bedrock)	5	150	170	74

In palaeovalley deposits, two bores in the Tanami Borefield have yielded up to 430 m^3-per-day over a 37 metre interval of unconsolidated coarse-grained sand and gravel within 86 metres of fluvial sediment infill. Transmissivity ranges from 47–70 m^3-per-day-per-metre, and the highest values occur in coarse sand and gravel. At some localities (such as Tripod Bore and Billabong Borefield) lateritic gravel deposits flank and underlie calcrete, with probable hydraulic connection between aquifers, but bores have yet to be drilled. Aquifer recharge is mainly from downward infiltration of rainfall and runoff and downward leakage from calcrete (Domahidy, 1990).

In palaeovalley calcrete aquifers the saturated thickness is slightly less than the total calcrete thickness, with watertable levels generally 3–6 metres below the surface. The saturated thickness averages 7 metres in the Tanami borefield and 15 metres in the Billabong borefield. Calcrete outcrops are up to 6 kilometres wide and may extend up to 35 kilometres down-valley, but these are likely to have more extensive subsurface distribution beneath surficial alluvium and aeolian sand. Test pumping of four bores at Tanami and two at The Granites indicates that transmissivity is high in these aquifers, i.e., 406–5,800 m^3-per-day-per-metre. Groundwater yields are typically about 850 m^3-per-day but can be as high as 1,700 m^3-per-day (Domahidy, 1990). Groundwater salinity in calcrete aquifers influences local vegetation types, providing a useful surface indication of calcrete groundwater salinity (Table 4.4) (Domahidy, 1990).

Table 4.4: Relationship between groundwater salinity and characteristic vegetation (after Domahidy, 1990).

GROUNDWATER SALINITY	VEGETATION TYPE
Fresh (<1,000 mg/L)	Ghost gums river red gums and mulga
Brackish (1,000–5,000 mg/L)	Spinifex and stunted ghost gums
Saline (>5,000 mg/L)	Spinifex and witchety bush (Acacia kempeana)

4.4.1.1. Tanami Palaeovalley Groundwater Storage

Bores at Tanami and Billabong borefields, the Rabbit Flat roadhouse and Tanami Downs homestead all obtain groundwater from calcrete aquifers. Six bores at Tanami yield 1.2 x 10^6 m^3-per-year and one at Billabong yields 0.5 x 10^6 m^3-per-year. These rates of groundwater extraction result in water level decline of about 0.1 metre-per-year. Domahidy (1990) numerically estimated the volume of stored groundwater in calcrete as 8 x 10^8 m^3, based on assumed average dimensions of 400 kilometres (length) x two kilometres (width) x ten metres (saturated thickness) and a specific yield of 0.1. The specific yield assumption was believed to be conservative based on figures of 0.2–0.3 from the Amadeus Basin (NT), Wiluna and Yalgoo (WA). Domahidy (1990) believed that palaeovalley alluvium groundwater resources were likely to be as large, or larger, than those calculated for the calcrete aquifers.

Recharge of palaeovalley aquifers occurs by infiltration of rainfall and runoff from significant rainfall events. During low intensity rainfall, water is lost by soil wetting or evapotranspiration with no infiltration. Based on estimates from similar terrain at Wiluna in Western Australia (Chapman, 1962), rainfall intensity of >50 millimetres in 48 hours is required to induce general runoff. Domahidy (1990) noted that between 1970 and 1990 Rabbit Flat recorded 50 millimetres of rainfall in 48 hours between one and five times-per-year, and 50 millimetres of rainfall in 24 hours between one and three times-per-year; good recharge conditions in the Tanami region were thus assumed. Domahidy (1990) calculated a recharge rate of 4.5 millimetres-per-year and a total recharge volume over the entire Tanami study area of 7.7 x 10^7 m^3-per-year (assuming 100% efficiency of drainage from non-palaeodrainage terrain to palaeovalleys). This volume estimate is equivalent to about 10% of the total storage reserves. Other recharge studies undertaken by Sanders (1972) at Wiluna suggested that 5% of high-intensity rainfall (equal to 1% of average annual rainfall) infiltrates to recharge calcrete aquifers.

In contrast to the optimistic recharge calculations of Domahidy (1990), Cresswell et al. (1999) derived more conservative recharge estimates based on ^{14}C and ^{36}Cl ages for groundwater in a palaeodrainage tributary to Lake McKay. This palaeovalley tributary is located south of the Tanami region in a more arid climate with average rainfall <250 millimetres and average evaporation >3,000 millimetres. The recharge rate was estimated to be <1 millimetre-per-year and the ^{36}Cl groundwater age showed a bimodal pattern with modern (Holocene) recharge waters distributed around the margins of the basin and most groundwater 80–100 thousand years old. These data imply that the last major recharge event occurred in the previous interglacial period of Marine Isotope Stage (MIS) Five. Finite ^{14}C ages, at variance with the ^{36}Cl ages, were explained by low recharge rates allowing diffusion of recent atmospheric carbon to the watertable. These data suggested that recharge only occurs during wet interglacial periods of the Quaternary climatic cycle. This finding is largely is consistent with surface water hydrological records of long-term monsoon intensity (Magee, et al., 2004; Magee, 2007) and major periods of recharge to the Great Artesian Basin (Radke et al., 2000; Kellett et al., 2003). Thus, for substantial periods (e.g., 80,000 to 10,000 years) no effective recharge has occurred, demonstrating that extraction of such groundwater exploits an ancient source, thereby mining a non-renewable resource.

4.4.1.2. Tanami Palaeovalley Groundwater Quality

Palaeovalley groundwater salinity in the Tanami varies from fresh (<1,000 mg/L) to very saline (~33,000 mg/L) but elevated salinity levels predominate because of the high rate of evapotranspiration, especially in low-lying downstream reaches where clay pans and salt lakes are common and the watertable is shallow.

Table 4.5: Tanami region palaeovalley groundwater chemistry showing selected ionic concentrations and ratios (after Domahidy, 1990)

AQUIFER TYPE	BORE LOCATION	Na	K	Ca	Mg	SiO_2	HCO_3	Cl	SO_4	NO_3	TDS	pH	Ca/Mg	Na+K/ Ca+Mg	HCO_3/ SO_4	HCO_3/ Cl
Calcrete	Rabbit Flat	138	32	74	60	93	332	247	118	40	960	7.4	0.75	0.79	2.22	0.78
Calcrete	Tanami Downs	205	25	50	51	86	366	245	92	96	1,020	8.0	0.60	1.42	3.12	0.87
Calcrete	Tanami Downs	85	34	52	48	76	292	118	67	89	1,080	7.7	0.65	0.70	3.45	1.44
Calcrete	Tanami Borefield	179	51	68	60	92	384	262	107	32	1,045	7.6	0.68	1.08	2.86	0.85
Calcrete	Tanami Borefield	241	51	70	68	80	326	398	137	54	1,295	7.5	0.62	1.29	1.89	0.47
Calcrete	Tanami Borefield	243	49	80	56		402	341	201	56	1,230	7.6	0.86	1.37	1.56	0.68
Calcrete	Billabong Borefield	746	115	138	132	86	315	1,261	529	34	3,110	7.8	0.63	1.99	0.47	0.14
Calcrete	Billabong Borefield	478	81	92	84	90	270	747	368	35	2,160	7.8	0.66	1.98	0.58	0.21
Calcrete	Billabong Borefield	3,170	340	180	390	91	628	5,044	2,444	43	11,870	7.4	0.28	3.55	0.20	0.07
Palaeochannel	Tanami Downs	218	58	51	54	55	310	310	144	9	1,015	7.3	0.57	1.57	1.69	0.58
Palaeochannel	Tanami Borefield	310	59	51	34	24	384	337	288	61	1,168	7.7	0.38	2.44	1.05	0.66
Palaeochannel	Tanami Borefield	264	53	148	80	32	384	496	335	12	1,640	7.2	1.12	0.99	0.90	0.45

Increasing groundwater salinity trends in Tanami region palaeovalleys include:

- From tributary to trunk palaeovalleys;
- From the periphery to the centre of trunk palaeovalleys;
- Downstream in trunk palaeovalleys; and
- With depth in palaeovalley aquifers.

There are similar trends in palaeovalley calcrete aquifers, with measured TDS levels ranging from 960–11,900 mg/L. The lowest salinity groundwater occurs in the upstream reaches of the palaeovalley system near Rabbit Flat, and the highest salinity groundwater occurs in the downstream section at Billabong (Table 4.5). The ratio of various ionic species correlates closely with salinity and therefore with residence time since recharge. Fresh groundwater contains the highest bicarbonate levels and brackish water has significantly higher amounts of chlorine and sulfate. Potassium levels are high, especially in brackish water, and the level of sodium plus potassium exceeds that of calcium plus magnesium; this ratio increases with salinity. Calcium to magnesium ratios are lowest at high salinity levels (0.28–0.86). Nitrate levels are 32–96 mg/L, and four groundwater samples exceeded the World Health Organisation limit for human consumption (45 mg/L). Silica levels are relatively high (76–93 mg/L) and are consistent with secondary silica precipitation in the calcrete aquifer. As the palaeochannel and calcrete palaeovalley aquifers are hydraulically connected, groundwater from these different aquifers has similar chemical compositions.

4.5. CANNING BASIN – GREAT SANDY DESERT

The Canning Basin underlies a large part of north-western Australia (>595,000 square kilometres of which 430,000 square kilometres are onshore) and contains up to 18 kilometres (thick) of Ordovician to Quaternary sedimentary rocks. Onshore, the basin is bounded to the north by the Precambrian Kimberley Block, to the south by the Pilbara and Musgrave Blocks and to the east by the Amadeus Basin, Arunta Block and Tanami Region. The Warri Arch, an area of shallow basement, separates the Canning and Officer basins to the south-east. Prolonged, though episodic, sedimentation in the Canning Basin has accumulated a significant thickness of Ordovician to Cretaceous rocks. Following the retreat of Early Cretaceous seas the region formed a large sub-aerial plain of low relief, which has existed throughout the Cenozoic (Yeates et al., 1984). Beard (1973) suggested that post-Cretaceous uplift of the Canning and Officer Basins was greater in the centre of the continent and established a watershed which trends south-west from south of Lake Disappointment to west of Lake MacKay. Topographic gradients trend down from this divide to the south and north-west, and palaeodrainage networks have developed accordingly (Figure 4.20). Van der Graaff et al. (1977) suggested that there is a preferred west to north-west trend of the major palaeodrainage network, parallel to the major structural elements of the underlying sedimentary basin. Beard (1973) suggested that incision of the palaeovalleys extended to 60 metre depth, which, in association with deep weathering implicated very wet early Cenozoic climate conditions and extensive stream flow.

The modern active drainage at the margin of the region includes the rivers of the Kimberley Block which flow to the sea via the Fitzroy and Ord Rivers, and Pilbara rivers which trend north to north-west in structurally controlled valleys towards the Indian Ocean. However, the Rudall River and Savory Creek flow north-east from the Pilbara to the Great Sandy Desert, terminating in Lake Dora and Lake Disappointment respectively. Similarly, the Sturt Creek flows parallel to the south-east Kimberly margin and terminates in the Great Sandy Desert at Lake Gregory. These active drainages – in receipt of episodic monsoonal and cyclonic rainfall – connect with two large palaeovalley systems which drain the Canning Basin and Great Sandy Desert region; the Canning and Mandora palaeovalleys (Beard, 1973).

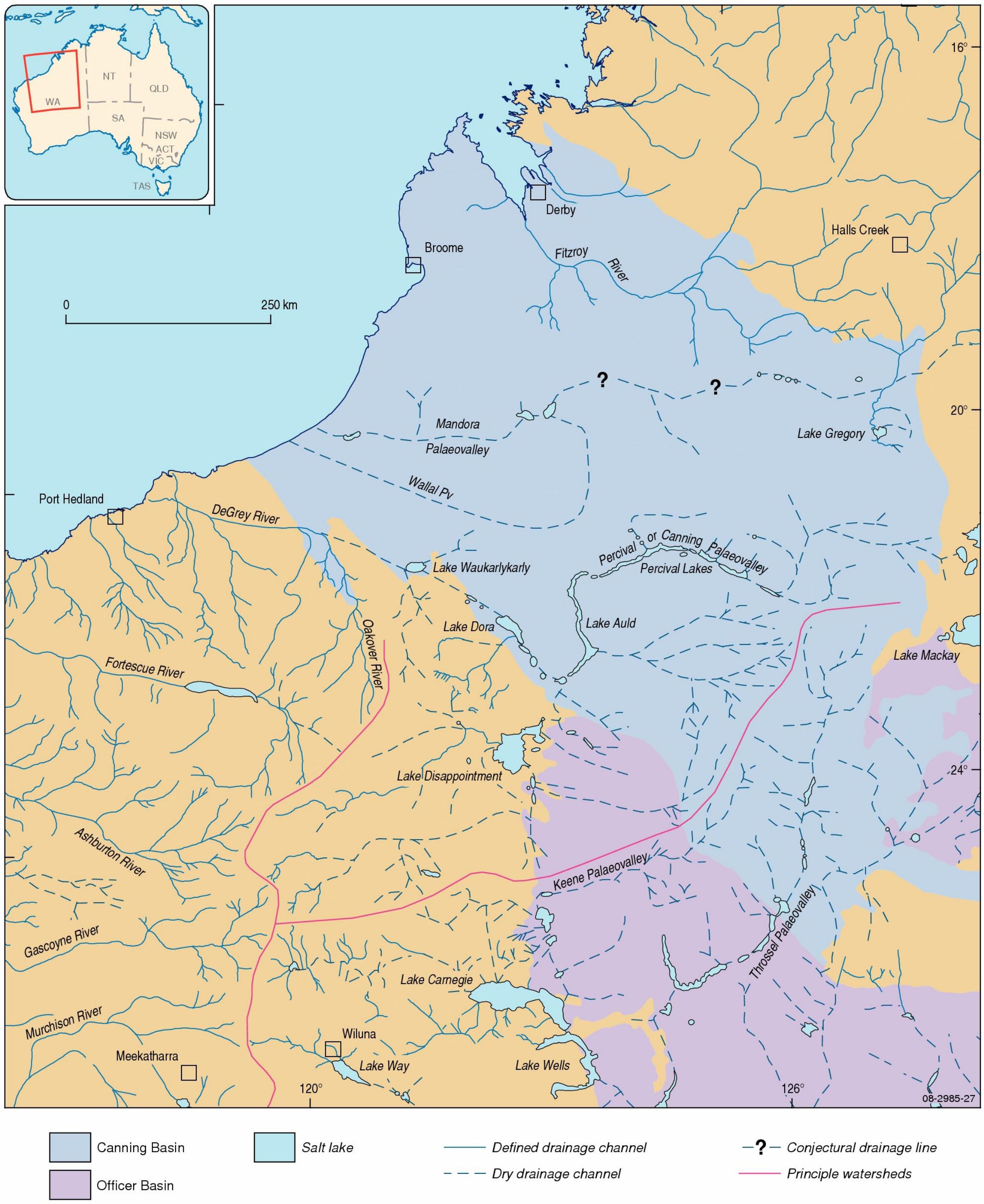


Figure 4.20: *Regional map of the Canning Basin in north-west Australia, highlighting the distribution of major palaeovalleys, salt lakes and the principle watersheds. Figure is modified from Beard (1973) and van der Graaff et al. (1977).*

The Canning Palaeovalley (Percival Palaeovalley of Van der Graaff, 1977) can be traced from the Stansmore Range north-west of Lake MacKay in a sinuous and generally westward course through the Percival Lakes, Lake Auld to Lake Blanche and Lake Dora then onto Lake Waukarlycarly and the Oakover River. Palaeodrainage systems from Lake Disappointment join the Canning Palaeovalley in the vicinity of Lake Blanche. The Lake Disappointment catchment receives drainage from all sides, including the active Savory Creek to the west and south-west and palaeovalleys to the south and east. Bunting et al. (1974) suggested that the Lake Disappointment palaeovalley ran north–south along the contact between Proterozoic and Phanerozic sedimentary rocks. Beard (1973) suggested that palaeodrainage to Lake Disappointment from the south was relatively short and that the Lake Keane palaeovalley joined the Lake Burnside to Lake Wells system flowing south to join the Throssel Palaeovalley. However Bunting et al. (1974) and Van der Graaff et al. (1977) suggested that the Lake Disappointment Palaeovalley had captured extensive palaeodrainage systems to the south including the Lake Burnside to Lake Wells and Lake Keane palaeovalleys, which formerly flowed south to join the Throssel Palaeovalley (Figure 4.21). Beard (2002) revisited this question in some detail and determined that the Lake Disappointment Palaeovalley includes Lake Burnside and the Lake Keane palaeovalley tributary and that the Carnegie system, south of Lake Burnside, has always flowed south and never connected to the Lake Disappointment Palaeovalley.

Beard (1973) regarded the Mandora Palaeovalley with more conjecture, and interpreted it to connect across the Great Sandy Desert in a westerly course from Sturt Creek (beyond its present terminus at Lake Gregory) to a clearly traceable palaeovalley at Mandora on the Eighty-Mile beach. Subsequently, Honey (1982) analysed NOAA–AVHRR data (National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer, see Section 5.3.2.3) and verified the mapped position of the Mandora Palaeovalley (from Beard, 1973) and its probable connection to the Sturt Creek catchment upstream of Lake Gregory. Honey (1982) used an enhanced composite of Band-1 and Band-2 data and a ratio of Band-1 to Band-2, and suggested that future work should compare thermal imagery with night thermal imagery. Van der Graaff et al. (1977) recognised the Wallal Palaeovalley between the Mandora Palaeovalley and the Percival Palaeovalley (Canning Palaeovalley of Beard, 1973) but gave no further discussion. Tapley (1988) and Tapley and Wilson (1985) provided a more detailed assessment of the Canning Basin Palaeodrainage and structural lineaments using NOAA–AVHRR satellite imagery. They showed that the Percival Palaeovalley is apparent on a Band-2 reflected near infra-red daytime image due to the presence of multiple high reflectance playas, which are elongated along much of the palaeovalley. Enhanced night-thermal imagery was more successful than daytime imagery at discriminating detailed patterns of structurally controlled trunk and tributary drainage for the three major palaeovalley systems in the Canning Basin. The night thermal data clearly identified palaeodrainages as relatively cold (lighter tones) alignments within warmer (darker) ironstone gibber and ferricrete uplands. Tapley (1988) suggested that the same signal is apparent even where dunefields mantle the palaeodrainage because the relatively thin sand layers of the dune swales (which overlie the ironstone-rich interfluves and uplands) contain sufficient reworked ironstone (up to 15%) to control the thermal signal.

No detailed descriptions of the palaeovalley infilling sediments of the Canning Basin and Great Sandy Desert region were reviewed. Yeates et al. (1984) suggested that valley calcrete deposits commonly form in the upper part of the sedimentary infill. This was later confirmed by a regional survey of groundwater potential in the southern Canning Basin (Commander, 1985).

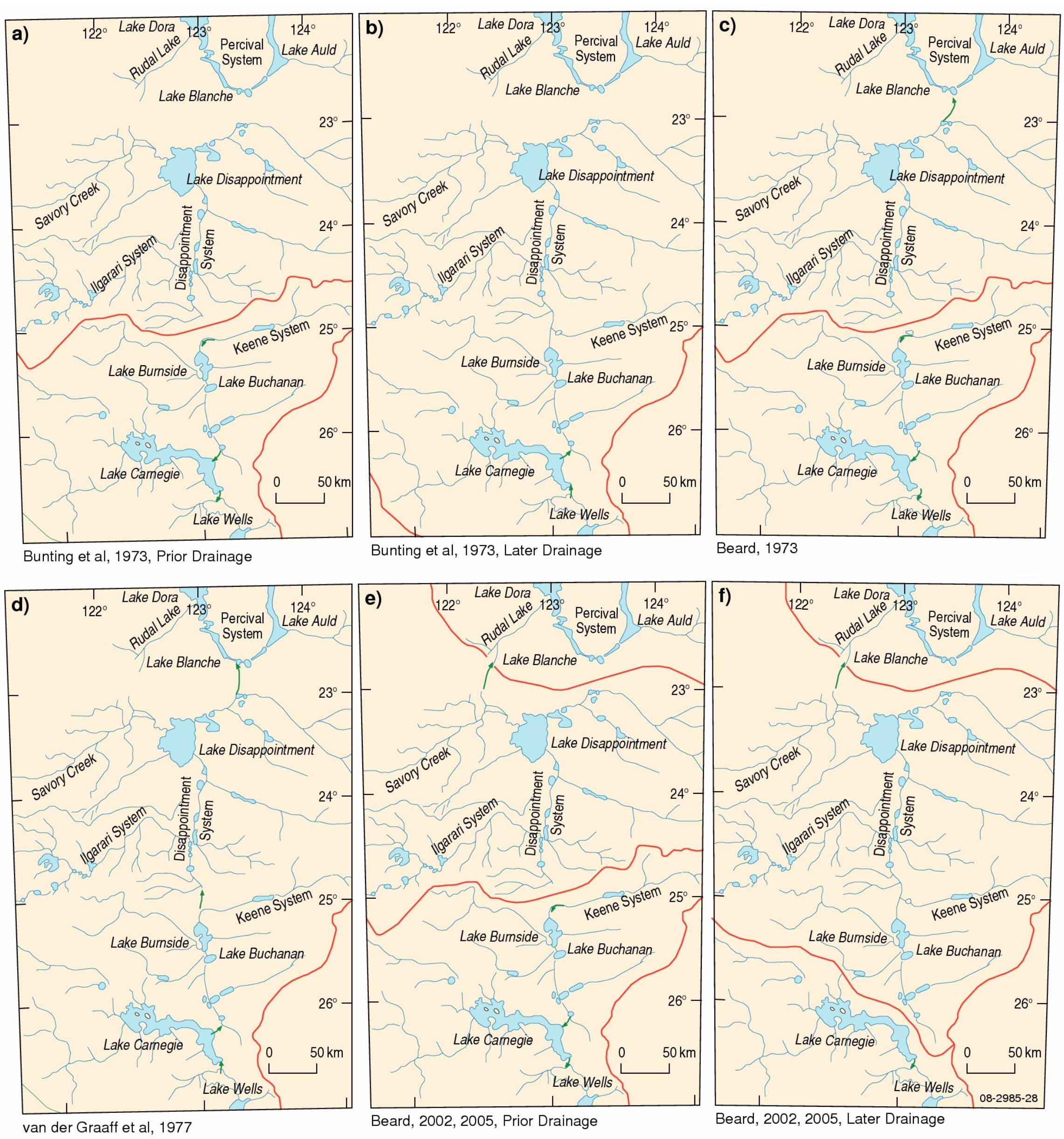


Figure 4.21: *Alternative reconstructions of the Lake Disappointment palaeodrainage network in Western Australia, showing how the interpreted location of palaeodrainage watershed lines has changed over-time. Figure incorporates drainage reconstructions proposed by various workers such as Beard (1973), Bunting et al. (1974), Van der Graaff et al. (1977) and Beard (2002).*

4.5.1. Canning Basin – Great Sandy Desert Groundwater Resources

Groundwater characteristics in the palaeovalley aquifers of this region are poorly understood. There are few published hydrogeological investigations and those that do exist concentrate on fractured rock and deeper sedimentary aquifers which are believed to supply fresher and more abundant water resources (Leech, 1979). Most studies have previously been concerned with potable water supplies for Aboriginal communities and pastoral stations. Yeates et al. (1984) mentioned that palaeovalley calcrete deposits are potentially valuable aquifers and were accessed by many bores along the Canning Stock Route. These bores once provided adequate and commonly potable water supplies, but most are now defunct. Commander (1985) reviewed potential groundwater resources for the Punmu Aboriginal community and its access routes through the surrounding region. This work concentrated on Canning Basin aquifers but suggested that palaeodrainage calcrete has the potential to supply potable water at relatively shallow depths, except close to playa discharge zones where higher salinity groundwater occurs. It seems likely that future mining ventures may extract usable saline water supplies for mine processing from palaeovalley aquifers.

4.6. PILBARA REGION

The Pilbara Craton hosts Archaean granitoid–greenstone rocks (3.6 to 2.8 billion years old) in the north, unconformably overlain by the Archaean and Proterozoic volcano-sedimentary sequences of the Hamersley Basin (2.77 to 2.38 billion years old) in the south. The Archaean greenstone terrane consists of metasedimentary and volcanic rocks intruded by variously deformed and metamorphosed granites that are, themselves, locally intruded by veins and dykes. The overlying Hamersley Basin contains folded and faulted mafic and felsic volcanic rocks, shale, siltstone, sandstone, conglomerate, dolomite and banded iron formations (BIF).

The Pilbara Craton is bounded and unconformably overlain by:

- Proterozoic metamorphic and igneous rocks of the Gascoyne Province (south-west);
- Proterozoic metamorphic and igneous rocks of the Paterson Province (north-east);
- Proterozoic metamorphosed sedimentary rocks of the Ashburton Basin (south);
- Palaeozoic and Mesozoic sedimentary rocks of the Canning Basin (north); and
- Palaeozoic to Quaternary sedimentary rocks and unconsolidated sediments of the Carnarvon Basin (west).

Cenozoic sediments and surficial deposits in the Pilbara are associated with weathering and erosion of the basement. Clastic and chemical sedimentation of weathered and eroded basement rocks has led to the formation of extensive sediment deposits on slopes and within drainages, including palaeovalley systems.

The main Pilbara drainage pattern, as well as the palaeodrainage pattern, is orientated towards the west-north-west following the dominant structural trend of the basement terrane (Figure 4.22). The Fortescue Plain, for example, is an elongate and relatively narrow alluvial plain which trends west-north-west between the Hamersley and Chichester Ranges. The Fortescue Plain was formed by selective erosion of the Wittenoom Dolomite along the course of the Fortescue River and its precursor drainage systems. The Pilbara drainage network has three main river systems, the De Grey, Fortescue and Ashburton rivers and their associated lateral tributaries and catchments. These major rivers traverse the Pilbara basement terrane and discharge to the Indian Ocean in wide braided channels across the coastal plain (which overlies the Carnarvon Basin) via a combination of direct ocean outlets and marshy flats (Ruprecht and Ivanescu, 2000). The main river valleys, including many of the tributaries, are characterised by palaeovalleys filled with sediments which have stratigraphic continuity and groundwater connectivity to valley side and slope alluvial and colluvial sediments.

The Pilbara has a semi-arid to arid climate. Rainfall patterns are highly variable and summer-dominant (mean annual value of 200–350 millimetres), and are generally derived from cyclones and thunderstorms. In the southern coastal sector, winter low-pressure frontal rains occur. Under this variable climatic regime all rivers are ephemeral but can carry large floods which may inundate valley floors, including palaeovalleys. Thus, unlike most other palaeovalley aquifer systems, recharge processes are dominated by surface runoff, and recharge rates are potentially large. Similarly, leakage from surface river flows can also contribute significant recharge to groundwater systems on the coastal plains, and surface water – groundwater connectivity occurs along palaeodrainage tracts from the bedrock terrane to the coastal plain zone (Ruprecht and Ivanescu, 2000).

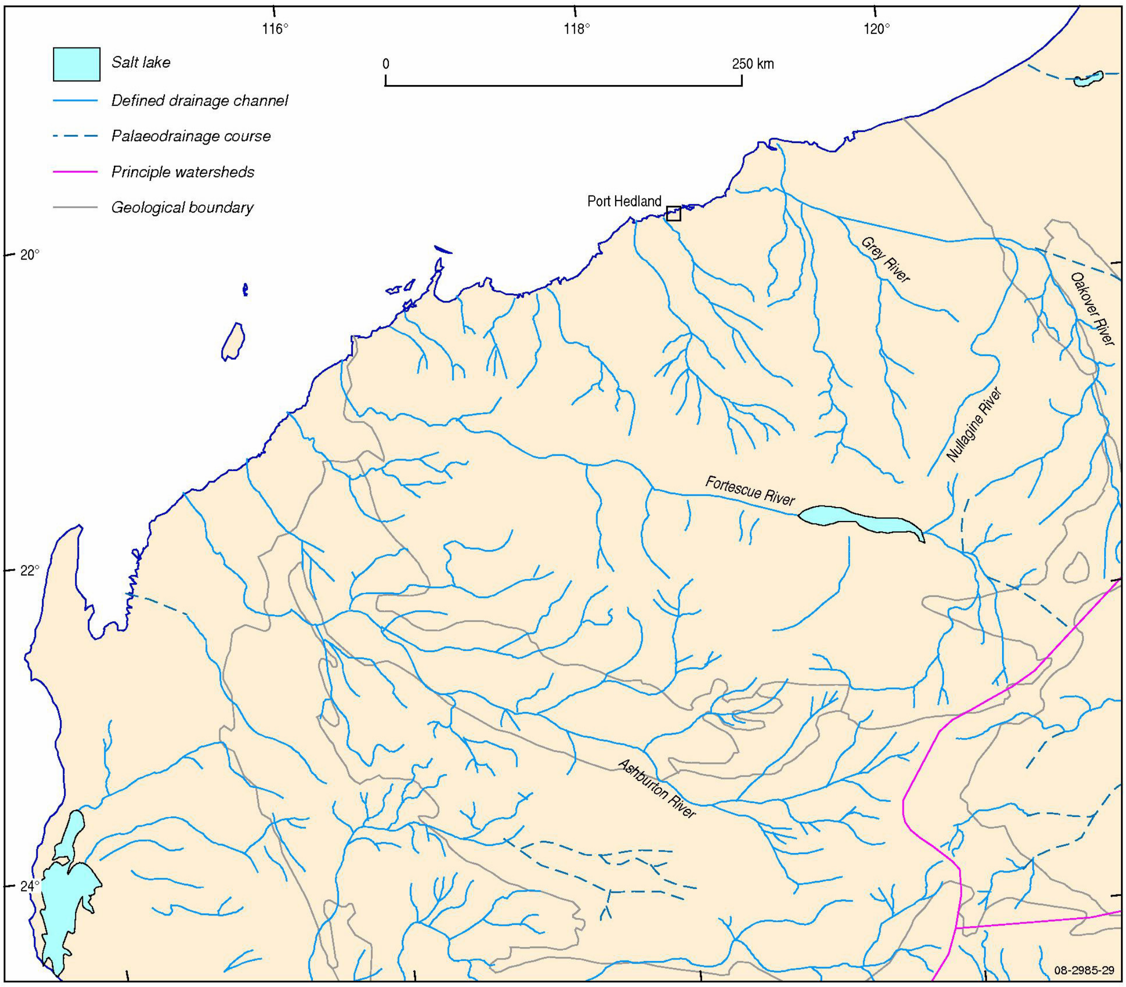


Figure 4.22: *Map of the Pilbara region in Western Australia highlighting the dominant west-north-west orientation of the modern drainage pattern, including the major river systems of the De Grey and Fortescue. Palaeodrainages within the Pilbara also follow this similar structurally controlled trend.*

The stratigraphic and sedimentologic characteristics of Pilbara palaeovalleys and their groundwater resources are relatively well-studied because some of the iron-rich sediment infill has been targeted for mining, and also because the abundant groundwater resources are used for town and mine water supplies (Figure 4.23). Palaeovalley sequences in the Pilbara are dominated by two types of chemically deposited sediment, namely the famous channel-iron deposits (CIDs) and calcrete. Other common sediment deposits are basal clastic-filled channels, clays and calcareous clays interbedded with calcrete and dolomite, lateral slope deposits and near-surface Quaternary alluvial sediments associated with the modern river channels. These palaeovalley infill sediments intertongue laterally and typically have interconnecting groundwater systems (Johnson, 2004).

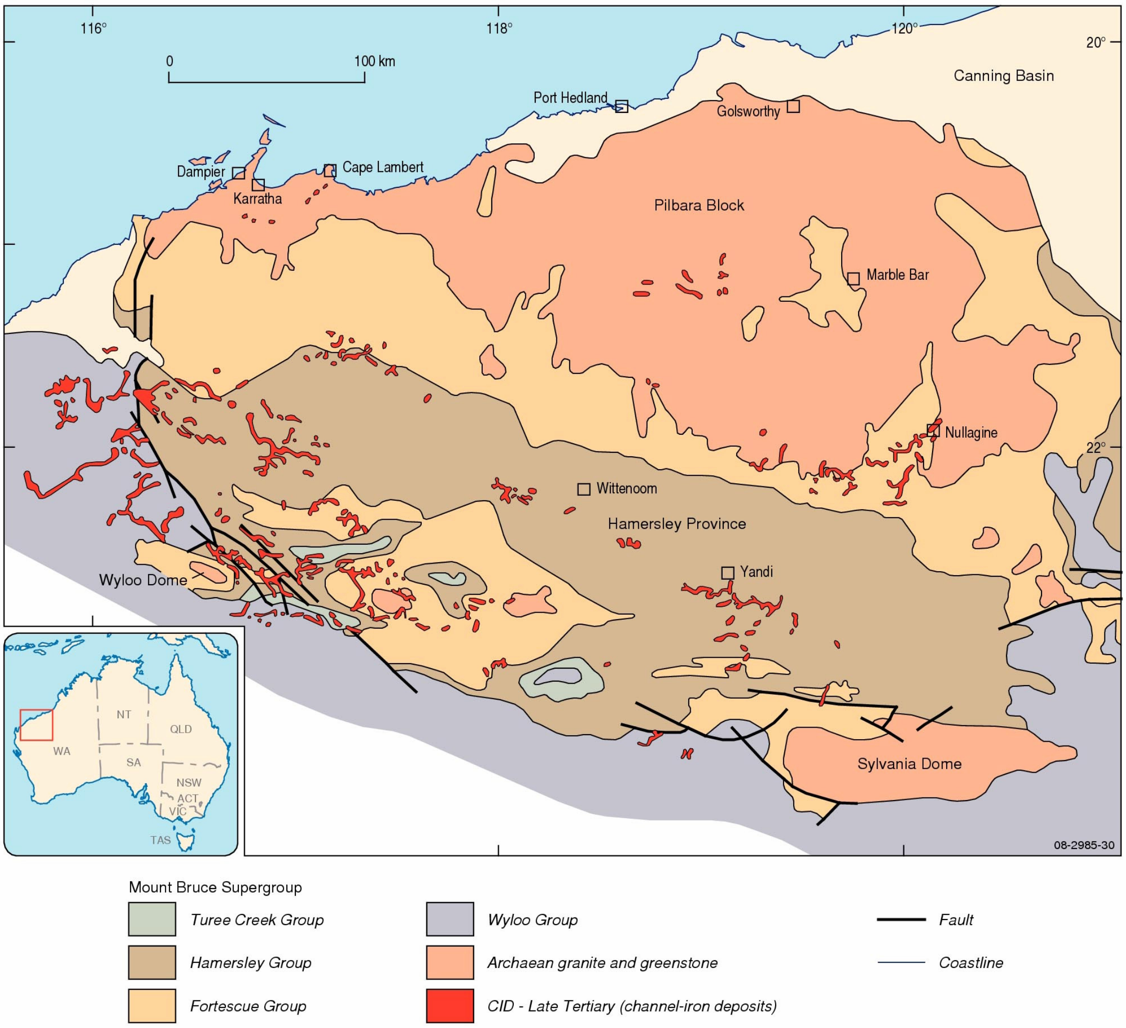


Figure 4.23: *Map of the main geological formations in the Pilbara region, and the location of major channel iron deposits (CIDs) which are hosted in palaeovalley sediment sequences. Figure is modified from Ramanaidou et al. (2007) and Stone et al. (2007).*

4.6.1. Western Fortescue and Robe Palaeovalleys

The Fortescue Plain extends northwards 450 kilometres from a steep erosion scarp of the Hammersley Ranges to the more gentle slopes of the Chichester Range. Much of the upper river catchment dissipates into a low gradient region of the plain, termed ‘The Marsh’, and from there the Fortescue River follows a braided course to Millstream where it diverts north-west into bedrock gorges (Barnett and Commander, 1985). The present course has formed by capture of the Fortescue system from the north-west, with the original valley oriented south of the Robe River (Barnett, 1981). The westernmost 90–100 kilometres of the Fortescue Plain has been investigated for groundwater resources as part of the West Pilbara Water Supply for towns such as Karratha, Dampier, Wickham and Roeburn (Davidson, 1969; Davidson, 1972; Barnett, 1981; Barnett et al., 1977; Barnett and Commander, 1985; Johnson, 2004). Here the plain is 10–25 kilometres wide and slopes gently from 345 metres AHD near Weelumurra Creek to about 315 metres AHD at the Robe–Fortescue watershed about 90 kilometres further to the west. Tributaries from the Chichester Range to the north follow defined channels which join the Fortescue system, whereas Hammersley Range tributaries from the south dissipate in a series of coalescing alluvial fans forming 5–10 kilometre-wide piedmont slopes. The western edge of the Fortescue Plain is dissected by the Robe River and its tributaries, and the incised Fortescue River has an alluvium-filled flood plain (~1 kilometre-wide) with several deep perennial scour pools which are fed by springs from the Millstream Dolomite aquifer (Barnett and Commander, 1985).

The Fortescue River valley is incised into Proterozoic Hammersley Basin rocks and follows the strike orientation of the less resistant Wittenoom Dolomite formation. The post-Proterozoic valley infill, which includes palaeovalley deposits, consists of a complex sequence of alluvial, colluvial and lacustrine sediments (Figure 4.24). These sediments range in age from Cretaceous to Holocene, although the chronological evolution is poorly constrained (Barnett, 1981; Barnett and Commander, 1985). The basal valley-fill unit is known from only two bores and consists of angular to rounded clasts of reworked Wittenoom Dolomite within in a narrow channel incised into the surrounding bedrock. This unit underlies the Robe Pisolite and is lithologically correlated to the Yarraloola Conglomerate, which outcrops outside of the Fortescue River Plain and is interpreted as Cretaceous (Williams, 1968) based on its similarity to Early Cretaceous marine deposits in the Carnarvon Basin (further west). Occupying a similar stratigraphic position below the Robe Pisolite are undifferentiated coarse sand, gravel and clay sediments infilling channels cut more deeply into the Proterozoic bedrock. Barnett and Commander (1985) identified these channels in a number of boreholes but were unable to determine their age or stratigraphic relationship as the channels are incised 60–70 metres below the other Cenozoic valley fill sediments, and are also well below the level of modern bedrock incision of the Robe River (by up to 56 metres) and Fortescue River (by up to 90 metres). A possible western outlet for these channels is thus unknown; they may represent tectonically disrupted parts of the former Fortescue River drainage further to the east.

The Robe Pisolite outcrops extensively and occurs widely in the subsurface of the Robe River and lower Fortescue valley (Barnett, 1981). It extends westward from the bedrock terrane into the subsurface coastal plain (Williams, 1968). The Robe Pisolite is compositionally diverse and includes massive to pisolite-bearing ironstone with minor layers of clay, ferruginous shale, pebbles, calcrete and calcareous clay. The unit has been extensively mined for iron-ore in the Robe River area since 1972. The pisolite material consists of goethite or goethite-haematite and it is variably cemented by goethite and limonite. Pisoliths are mostly <2 millimetres diameter but can range up to 12 millimetres. The Robe Pisolite formed in a fluvial environment, although considerable debate initially surrounded the actual genetic process; previous theories have included direct precipitation, replacement of fluvial sediments or a combination of these processes (Barnett, 1981). More recent research has recognised that the Robe Pisolite (now the Robe Formation) represents a channel-iron deposit (CID), one of three distinct types of mineable iron-ore found in the Pilbara (Morris and Ramanaidou, 2007; Ramanaidou et al., 2003):

- **Bedded-iron deposits** (BID), which are banded-iron formation (BIF)-hosted haematite and haematite-goethite deposits;
- **Channel-iron deposits** (CID), which are iron-rich goethite haematite fluvial deposits; and
- **Detrital-iron deposits** (DID), which are minor haematite-goethite colluvial/alluvial deposits derived due to erosion of BID.

Channel iron deposits are globally rare, and the only other significant CID region outside the Pilbara is situated in Kazakhstan, where Mid Oligocene fluvial, lacustrine and lacustrine-deltaic deposits are mined (Ramanaidou et al., 2003).

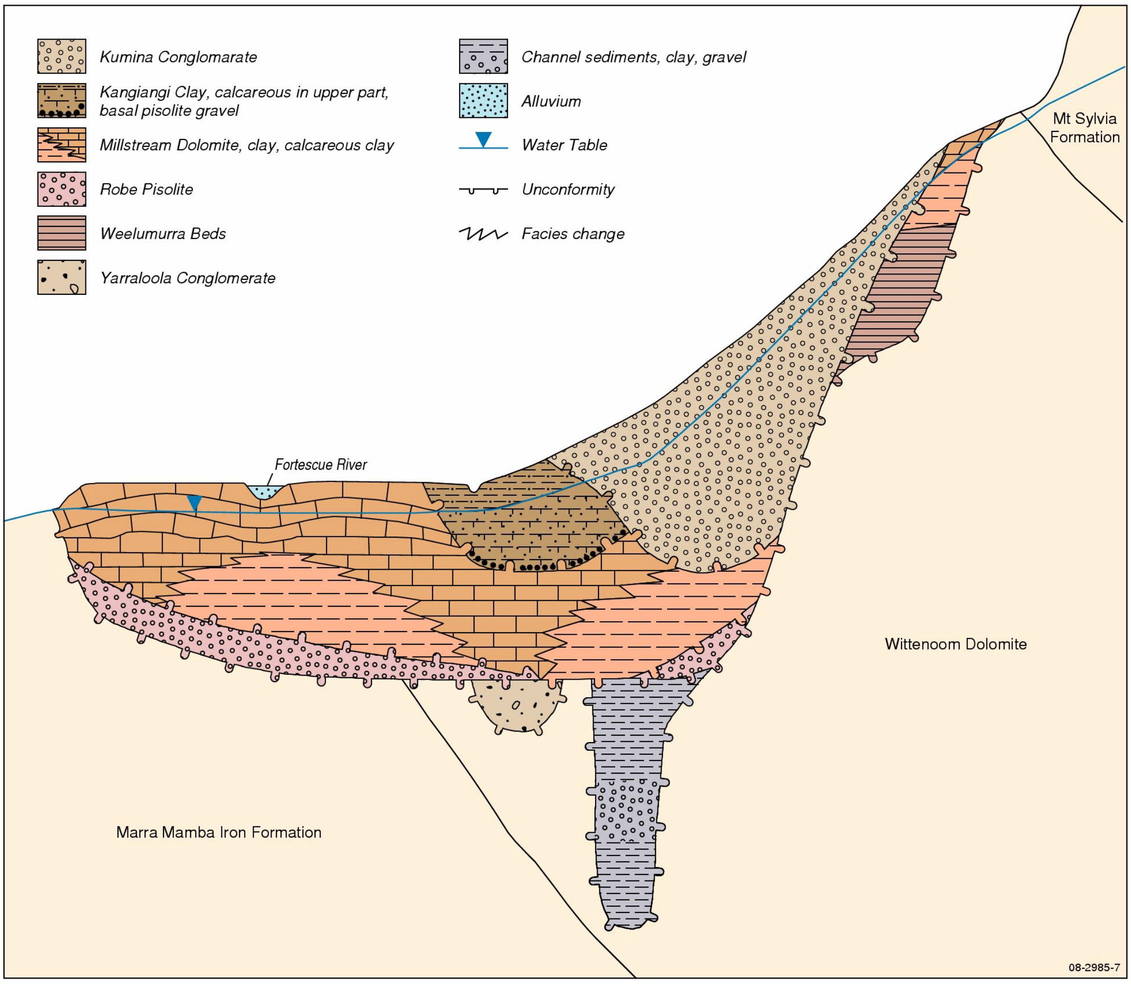


Figure 4.24: *Schematic cross-section of the Lower Fortescue River valley showing the complex stratigraphic relationship of the various Cretaceous to Holocene sediment deposits which infill the valley. Figure is modified from Barnett and Commander (1986) (Figure 5).*

Channel iron deposits occur widely in the Pilbara (Figure 4.23). They represent palaeovalley infill deposits of variable thickness (up to 100 metres thick) which are typically <1 kilometre-wide, ranging up to several kilometres wide in some areas. The Robe Palaeovalley contains the longest individual deposit with CID discontinuously preserved over 150 kilometres. CIDs are commonly preserved in the middle reaches of the Robe Palaeovalley as mesas or sinuous ridges (inverted relief) in the central part of the palaeovalley. The Robe CID includes massive bedded and altered types of goethitic mudstone, fine haematite-goethite gravel and intraformational conglomerate. Ooidal granular forms predominate and comprise a diverse porous goethitic matrix which contains:

- Pelletoids with goethitic cortices around haematitic nuclei (often fossilised wood);
- Abundant coarse goethitic wood fragments;
- Variable proportions of peloids; and
- Minor pisoids.

Robe CID pelletoids are more spherical and have more regular layering and smaller cores than CID from the Yandi deposit in the Marillana palaeovalley (Section 4.6.2) (Ramanaidou et al., 2003). In the western Fortescue Palaeovalley the Robe Formation is 3–33 metres thick and consists of massive ironstone, cemented pisolites and layers of clay and shale with pebbly shale common at the base. The massive ironstone is siliceous and goethitic and contains irregular vughs, 0.1–30 centimetres diameter, which are commonly lined with limonite or chalcedony (Barnett, 1981; Barnett and Commander, 1985).

The Millstream Dolomite is a major palaeovalley infill unit that unconformably overlies the Robe Formation and extends as outcrop or in the subsurface over much of the western Fortescue Plain (Figure 4.25A and Figure 4.25B). On the southern side of the plain the unit is unconformably overlain by the Kumina Conglomerate and to the east by the Kangiangi Clay. The Millstream Dolomite is overlain by a thin veneer of gravel-rich sand or pedogenic red clay (gilgai-patterned) across much of the Fortescue Plain. The surface is also marked by small sink holes and unusual circular features which Barnett (1981) attributed to doming, caused by displacement of the surrounding rock mass due to carbonate precipitation at the watertable. The Millstream Dolomite consists of up to 46 metres of variably coloured (white, pink, yellow-buff or marbled) and textured dolomite and layers of silcrete, illite–nontronite clay, calcareous clay and conglomerate. The formation ranges from soft and earthy to hard and massive. Dolomite predominates below the watertable and calcareous dolomite above the watertable, which is presently located at about 294 metres AHD. Veins and beds of secondary silica occur throughout but are concentrated in two layers, at the watertable and also at 310 metres AHD – probably indicating a past watertable level. Vughs and cavernous voids (up to 0.5 metre-wide) are also common at the watertable and are commonly lined with silica. A layer of mottled yellow/white/greenish limonitic silcrete up to 6 metres thick occurs near the base of the unit, and may contain clasts of the Robe Formation. The lower 10–15 metres of the unit consists of one or more layers of green, dark-green, blue-grey or yellow illite–nontronite clay; this is the only facies of the Millstream Dolomite which occurs along the southern valley margin (Figure 4.25B).

The Millstream Dolomite probably formed in mixed lacustrine and valley calcrete environments. The latter formed as carbonate deposits which precipitated from groundwater, replacing valley-fill deposits in the near-surface arid conditions due to concentration of calcium carbonate by evapotranspiration (Sanders, 1974). Extensive diagenetic alteration of the original lacustrine and alluvial limestone and clay has resulted in the development of nodular, veined and brecciated textures. Dolomitisation and silicification have also occurred commonly at or below the watertable. The magnesium-rich groundwater responsible for dolomitisation was probably derived from the underlying Wittenoom Dolomite (Barnett, 1981; Barnett and Commander, 1985). The age of the Millstream Dolomite is poorly constrained. Barnett (1981) considered it a Late Tertiary to Pleistocene formation based on molluscan fossils. Barnett and Commander (1985) later suggested a probable Mid to Late Tertiary age and probable correlation to the Oakover Formation palaeovalley calcrete in the eastern Pilbara.

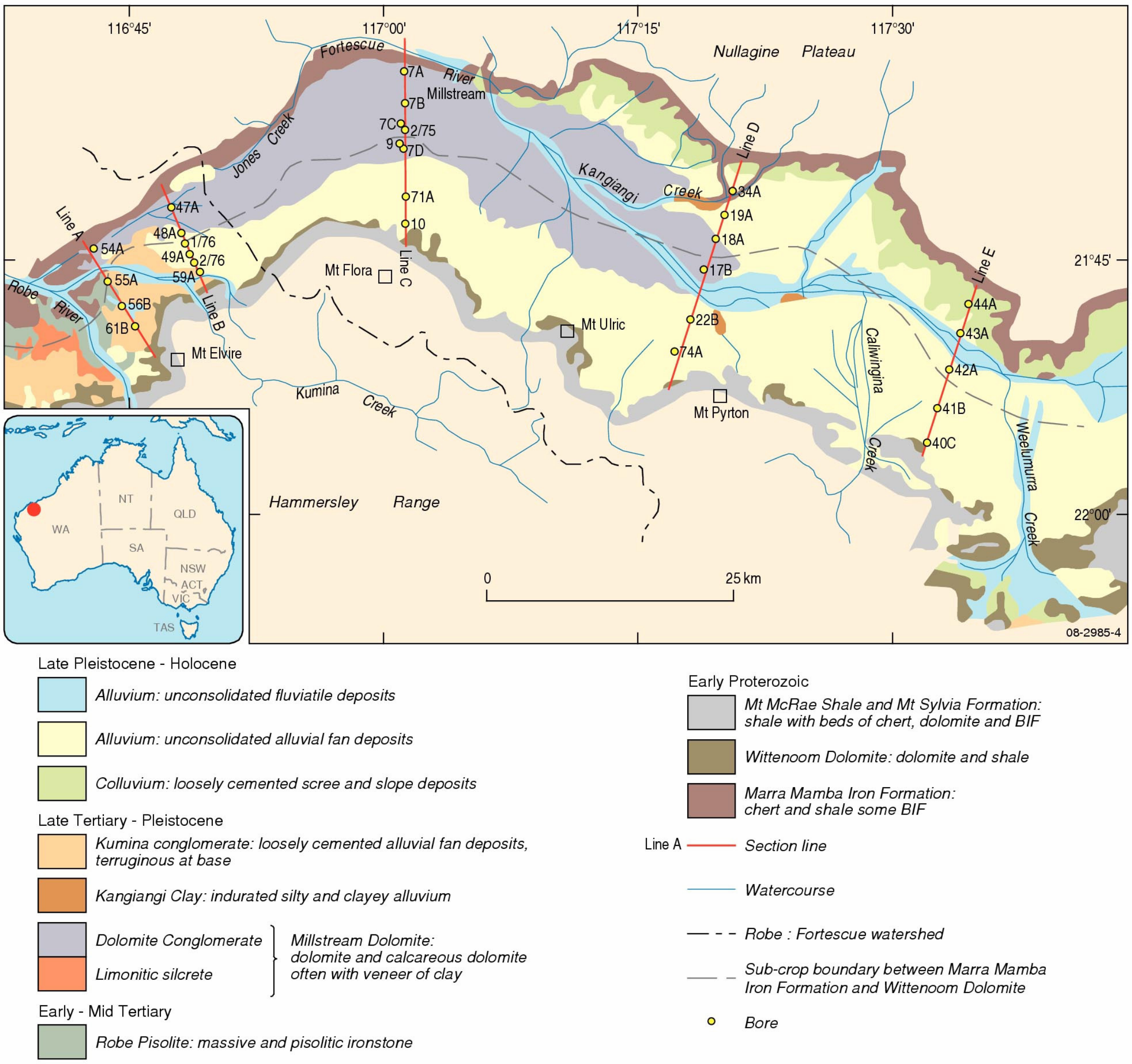


Figure 4.25: (A) *Geological map of the Lower Fortescue Valley highlighting the widespread location of the Millstream Dolomite. Extensive drilling transects across the valley (Lines A–E) have yielded considerable detail about the nature of the palaeovalley infill sequence, as shown in Figure 4.25 (B). Figure modified from Barnett and Commander (1986) (Figure 3).*

Other Cenozoic stratigraphic units have been recognised and described from the western Fortescue Plain (Barnett, 1981; Barnett and Commander, 1985). These are mainly alluvial or colluvial deposits derived from the southern slopes of the Hammersley Range, unconformably overlying the palaeovalley deposits. They have lateral connection to the palaeovalley aquifers and are important components of the groundwater system. The oldest of these units are the Weelumurra Beds, which comprise up to 34 metres of dark grey pyritic lacustrine clay formed behind a bedrock bar in the ancestral Weelumurra Creek. The Weelumurra Beds are overlain by gravely conglomerate and calcrete correlated to the Millstream Dolomite but their age relative to the Robe Formation, in a similar stratigraphic position, is unknown (Barnett, 1981; Barnett and Commander, 1985). The Kangiangi Clay occurs in the eastern Fortescue Plain and unconformably overlies the Robe Formation and Millstream Dolomite palaeovalley sediments, with ferruginous pisolithic gravel marking the unconformity. It consists of up to 47 metres of red-brown to yellow-brown, well bedded, silty clay with sand and gravel beds cemented by iron oxides near the surface and by silica and carbonate below the watertable. The Kangiangi Clay is interpreted as a Late Neogene lacustrine deposit, although it contains minor alluvial material (Barnett, 1981; Barnett and Commander, 1985). The Kumina Conglomerate forms the piedmont slope of the Hammersley Range where it unconformably overlies basement rocks and various Cenozoic units (including palaeovalley sediments). It probably also partly interfingers with the Kangiangi Clay. The Kumina Conglomerate, a Neogene alluvial fan deposit, comprises up to 90 metres of sub-rounded to rounded, moderately sorted, boulders, cobbles, gravels and sand in a brown silty-clay matrix, with minor interbeds of silty clay and a ferruginous basal layer (Barnett, 1981; Barnett and Commander, 1985).

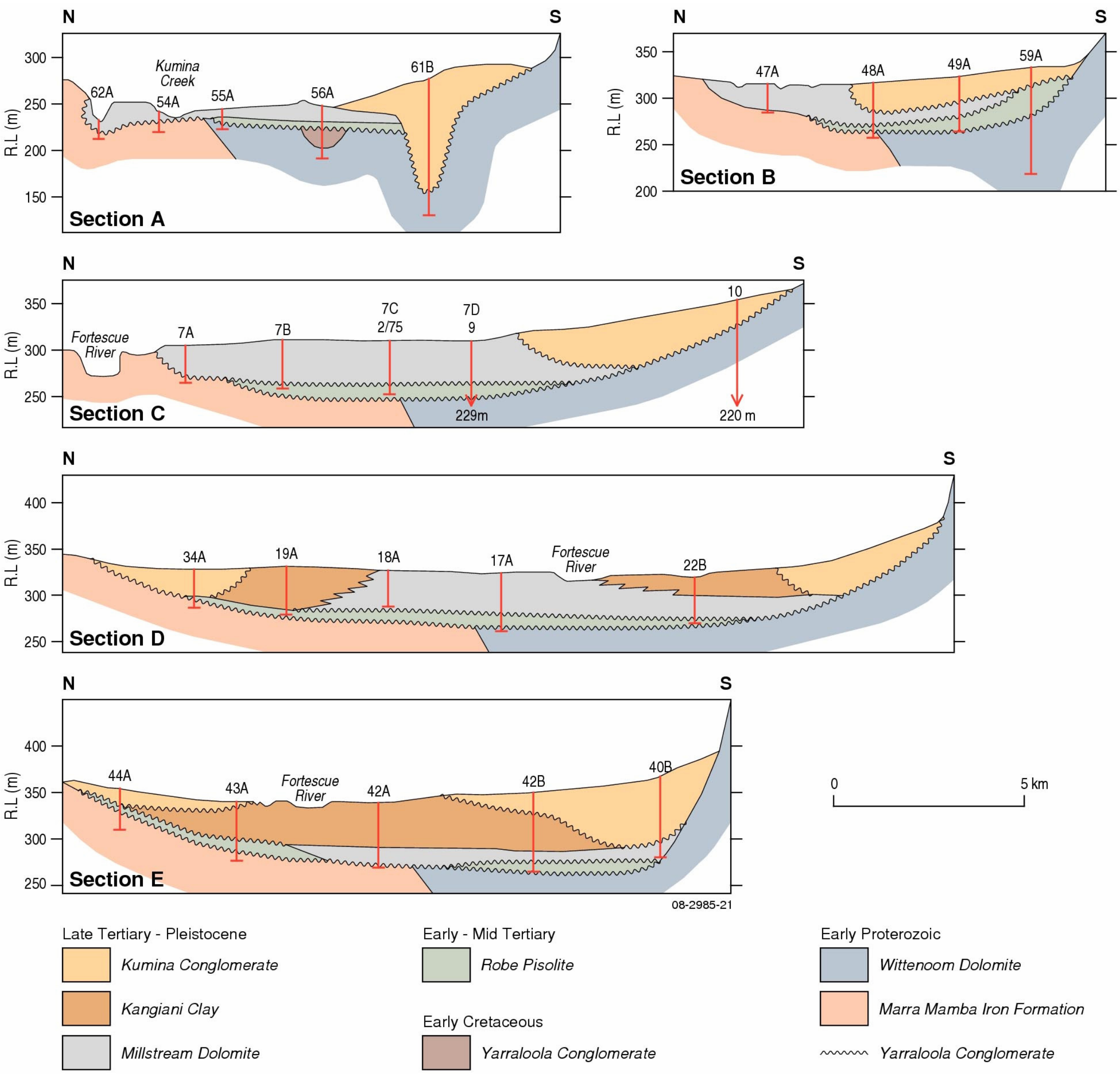


Figure 4.25: (B) *Interpreted cross-sections through the Cenozoic sediment pile which has infilled the Lower Fortescue Valley in the Pilbara. The location of these drilling transect lines is shown on Figure 4.25(A). Note the variable valley profile shapes and the widespread nature of the Millstream Dolomite unit. Figure is modified from Barnett and Commander (1986).*

4.6.1.1. Groundwater in the Fortescue Palaeovalley

As for other Pilbara rivers, inflow to the Fortescue system is dominated by runoff from summer cyclones or thunderstorms. Recorded annual flow rates vary widely from 2.8 x 10^6 m^3 (1968–1969) to 1238 x 10^6 m^3 (1975–1976), with the latter largely due to widespread rainfall from Cyclone Joan in December 1975. Salinity levels have previously ranged from 93–3,045 mg/L TDS with a flow-weighted average of 497 mg/L. The highest TDS concentrations occur in low flow years due to enhanced contribution from spring-fed groundwater, which has higher salinity due to concentration by evaporation from the aquifer (Barnett and Commander, 1985). The Cenozoic units recognised in the western Fortescue Plain, including the palaeovalley infill sediments, represent a single interconnected groundwater flow system, with varied hydraulic properties in different aquifers. The main aquifers are the palaeovalley sediments of the Robe Formation and the Millstream Dolomite and the piedmont Kumina Conglomerate (Barnett and Commander, 1985). The watertable slopes towards the north-east (up-valley in the Fortescue Plain) from the eastern boundary (Weelumurra Creek) of the Western Fortescue Plain (as studied by Barnett and Commander, 1985) indicating a likely lack of groundwater throughflow from the Eastern Fortescue Plain.

The Robe Formation aquifer is a vuggy pisolitic ironstone unit with interbedded clay, and is confined in the Western Fortescue Plain by the Millstream Dolomite or the Kangiangi Clay. The saturated thickness is generally <10 metres, with a maximum thickness of 18 metres. Transmissivity is lower than for the Millstream Dolomite but bore yields can be up to 1.7 x 10^3 m^3-per-day.

The Millstream Dolomite aquifer extends over most of the valley, except for the north-east margin, and consists of dolomite, calcrete and silcrete with interbedded clay (Davidson, 1969, 1972; Barnett et al., 1977; Barnett and Commander, 1985). Only clay occurs along the southern valley margin and in the eastern section near Weelumurra Creek. The dolomite, calcrete and silcrete have well developed secondary porosity in the form of solution cavities, especially at the watertable. The aquifer is confined in the east by the Kangiangi Clay and unconfined elsewhere, with the greatest saturated thickness near the valley centre (up to 33 metres) and bore yields as high as 5.5 x 10^3 m^3-per-day.

The piedmont Kumina Conglomerate aquifer occurs along the southern flank of the valley and across the valley at Weelumurra Creek. It consists of poorly sorted gravel interbedded with clay. The aquifer is unconfined with limited saturated thickness, rarely up to 40 metres thick. There is a downward head gradient towards the underlying Millstream Dolomite except where the Kumina Conglomerate is perched above the Kangiangi Clay. Transmissivity is much lower than for the Millstream Dolomite and maximum bore yields are <0.6 x 10^3 m^3-per-day. The aquifer characteristics of the basal units of the Yarraloola Conglomerate and other undifferentiated channel deposits are poorly known. The maximum bore yield is 1.6 x 10^3 m^3-per-day. The nature of fractured and weathered bedrock aquifers is also poorly understood but transmissivity values are much lower than for the Cenozoic aquifers, except in places where enhanced porosity has developed due to secondary solution cavities in the Wittenoom Dolomite.

The Millstream Dolomite is the major Fortescue Palaeovalley aquifer and has been extensively exploited for the West Pilbara Water Supply since 1969. For example, the annual abstraction level reported for twelve production bores by Barnett et al. (1977) was 9 x 10^6 m^3. Barnett and Commander (1985) had difficulty in determining aquifer characteristics because extremely high transmissivity in the Millstream Dolomite rendered pump tests ineffective. An unconventional approach was used to estimate specific yield, whereby downhole stereoscopic colour photography and gamma logs from five drillholes were combined with laboratory-determined porosity and specific retention data (Barnett et al., 1977). Porosity is the dominant controlling factor for specific yield, and the secondary porosity of the Millstream Dolomite is highly variable both vertically and horizontally. Using this method, the estimated average specific yield for the Millstream Dolomite was reported as 0.1 (Barnett and Commander, 1985).

Bore hydrographs from the unconfined section of the Millstream Dolomite aquifer demonstrate that river flow is the major source of recharge. The watertable response to river flow decreases in magnitude away from the river channel and the time-lag of response increases. Comparative records from flood events that lacked local rainfall clearly demonstrate that flood recharge dominates over direct rainfall recharge. The recharge volume for the summer of 1975–1976 (as calculated from watertable rise and an assumed specific yield of 0.15) was 49 x 10^6 m^3 which is more than three times the annual spring-flow discharge of 15 x 10^6 m^3. Recharge also occurs directly from rainfall across the outcropping aquifer surface (where unconfined) and from lateral stream runoff from the Hamersley and Chichester Ranges. Barnett and Commander (1985) used chlorine ion ratios of rainfall and groundwater to determine that direct rainfall recharge is low, but significant recharge potential exists from Caliwingina Creek (7.7 x 10^6 m^3) and Weelumurra Creek (16.6 x 10^6 m^3). These creeks directly recharge the Kumina Conglomerate via vertical infiltration through anastomosing gravel beds and lateral flow to the Millstream Dolomite occurs at Caliwingina Creek, although is less certain for Weelumurra Creek. Davidson (1972) investigated the possibility of artificial recharge of the Millstream Dolomite by diverting Fortescue River flow onto the aquifer over the left bank of the river by a low barrage. His conclusions were generally pessimistic about the efficacy of such a scheme and raised questions about potential salinity increases due to evaporation from the impoundment, and about the introduction of suspended solids into the cavernous aquifer system.

Aquifer isopotentials reported by Barnett and Commander (1985) indicated westward groundwater flow along the Fortescue Valley, sub-parallel to the river, from Weelumurra Creek to spring discharge near Millstream. Lateral groundwater flow from the valley flanks occurs at a steeper hydraulic gradient due to reduced hydraulic conductivity and aquifer thickness. West of Millstream a groundwater divide in the plain separates groundwater discharging into the Fortescue and Robe Rivers. The borefield is located near the spring discharge so abstraction has not altered the groundwater flow direction, but it has steepened the hydraulic gradient. Just south and west of Millstream the watertable is relatively flat, which reflects the high aquifer transmissivity.

Barnett and Commander (1985) estimated total groundwater storage in all Cenozoic aquifers by applying an average specific yield of 0.1 to the average saturated aquifer thickness and derived an overall volume of 1,700 x 10^6 m^3, of which 1,400 x 10^6 m^3 has salinity <1,000 mg/L (Table 4.6).

Groundwater salinity is lowest (300–400 mg/L TDS) in the Kumina Conglomerate and in the Millstream Dolomite adjacent to recharge zones near Weelumurra and Caliwingina Creeks. Along the valley flanks, peripheral recharge maintains salinity levels of 500–1,000 mg/L in the Millstream Dolomite, rising to 1,000–1,500 mg/L in the central valley where recharge is dominated by river flow. Barnett and Commander (1985) attributed higher salinity water sourced from river-flow to the concentration effect of the evapotranspiration process along the river after minor floods, and subsequent flushing of salts into the aquifer by large floods even though these have low salinity water (200–300 mg/L). Groundwater composition is dominated by sodium, magnesium, and calcium cations and bicarbonate and chlorine anions and, typical of calcrete aquifers, is mostly hard (200–300 mg/L total hardness expressed as CaCO3) or very hard (>300 mg/L total hardness as CaCO3). The nitrate concentration in the Millstream Dolomite is variable, generally 5–10 mg/L but may be up to 32 mg/L.

Table 4.6: Storage estimates for fresh groundwater (<1,000 mg/L TDS) within Fortescue Palaeovalley Cenozoic aquifers (from Barnett and Commander, 1985).

AQUIFER	AREA (km^2)	STORAGE PER UNIT AREA	STORAGE (10^6 m^3)
Millstream Dolomite (unconfined)	250	1.5	375
Millstream Dolomite (unconfined)	200	1.5	300
Millstream Dolomite (confined)	450	1.5	675
Millstream Dolomite (confined)	50	1.5	75
Robe Formation	150	1.0	150
Kumina Conglomerate (Weelumurra)	120	1.0	120
Kumina Conglomerate (Kumina)	60	1.0	60

Aquifer discharge is mainly by spring flow to the Fortescue River, with the main outlets at Deep Reach Pool and Millstream Spring discharging 10.3 x 10^6 m^3 and 3.8 x 10^6 m^3 respectively. Barnett and Commander (1985) reported that smaller springs west of Millstream had ceased to flow due to previous abstraction from the aquifer. Barnett and Commander (1985) used the Darcy equation, complicated by uncertain transmissivity values, to estimate groundwater outflow from the Millstream Dolomite to the Proterozoic bedrock at 1.5 x 10^6 m^3, i.e., considerably less than the total spring outflow. The storage-to-discharge ratio was estimated at about 100 years for spring discharge (Barnett and Commander, 1985). In 1983–1984 the annual groundwater abstraction rate was 10 x 10^6 m^3; the total abstraction volume of 92 x 10^6 m^3 from 1969–1982 lowered the watertable in the Millstream Dolomite by 0.23 metres, equal to storage depletion of about 23 x 10^6 m^3. The lowered watertable led to reduced spring flow into Deep Reach Pool and dried some smaller springs further west. Millstream Spring has been supplemented by a bore to protect groundwater-dependent ecosystems with 3.3 x 10^6 m^3 pumped in 1981–1982 (Barnett and Commander, 1985). Groundwater abstraction volumes from the Millstream Spring were subsequently reduced following supplementation of the water supply from the Harding River Dam in 1982. However, the West Pilbara Water Supply was wholly sourced from Millstream between 2000 and 2004, when a filtration system was installed at the Harding River Dam and again in 2008 due to drought-induced low water levels.

4.6.2. Yandi–Marillana Palaeovalley

The Marillana Palaeovalley is a Hammersley Range tributary of the Fortescue system in the eastern Pilbara which contains abundant channel iron deposits (CID), extending over at least 90 kilometres. The deposits have been mined at Yandi by BHP–Billiton (BHPB) since 1991 and studied in considerable detail, e.g., Hall and Kneeshaw (1990); Morris et al. (1993); Morris and Ramanaidou (2007); Ramanaidou et al. (2003); Kneeshaw (2003); Stone et al. (2002); Stone et al. (2003). These and other studies have included petrological and geochemical characterisations, and sedimentology, stratigraphy and facies analysis. The widespread focus of previous work has resulted in complex and often confusing nomenclature, with multiple stratigraphic and lithologic names and acronyms. It is beyond the scope of this review to resolve the confusion of various descriptive classification schemes. The following summary is chiefly derived from recent stratigraphic analysis undertaken by Kneeshaw (2003), based on BHPB mine-pit sections and exploration drillholes.

The CID in the Marillana Palaeovalley was originally named the Marillana Pisolite. This sedimentary sequence was believed to be significantly different from the Robe Pisolite mainly because it has a different spatial distribution. The CID are now included in the Marillana Formation, which comprises all fluvial sediments in the meandering Marillana Palaeovalley including tributary drainage systems such as Yandicoogina and Weeli Wolli (Kneeshaw, 2003). In the main palaeovalley system, the sediment fill is up to 120 metres thick and extends along-strike for more than 90 kilometres, ranging in width from 400–1,100 metres. Tributary valleys are smaller and have less sediment infill. The palaeovalleys are incised into Proterozoic Hammersley Group rocks and the Marillana Formation is disconformably overlain by calcretised lacustrine carbonates and unconsolidated alluvium and colluvium. The Marillana Formation crops out as a series of low mesas along the valleys (Stone et al., 2002) and is divided into three members, each with further internal subdivision (Kneeshaw, 2003):

The **Munjina Member** is up to 40 metres thick and consists of the Basal Conglomerate unit and the Basal Clay unit; these vary in thickness and composition across and along the channel. The Basal Conglomerate is 0–20 metres thick and consists of matrix- and clast- supported, poorly to moderately sorted conglomerate. Clasts are subangular to rounded and mostly 1–3 millimetres in diameter, rarely ranging up to boulder-sized fragments. The clasts are compositionally diverse and include fragments of BIF, chert, dolerite, shale and claystone in a white–grey–pink clay matrix, which may be partly silicified in places. Locally, mid-channel greyish black silt and clay layers occur, which can be pyritic and organic-rich with preserved charcoal and pollen. The Basal Conglomerate grades to the overlying Basal Clay which consists of 0–20 metres of massive, pale yellow to yellowish brown and white or red–pink kaolinite with minor thin layers of yellow goethite-bearing clay, altered CID (in mid-channel zones) and clay-matrix supported conglomerate. The Basal Clay is gradational with the overlying CID units and large cavities may occur at the contact.

The **Barimunya Member** is the main CID unit. It has maximum thickness of 50–70 metres and consists of two sub-units: the Upper CID and the Lower CID – this subdivision is attributed to groundwater alteration of the CID below the watertable. The unaltered Upper CID consists of 25–45 metres of red-brown haematite-goethite granules with preserved sedimentary structures, including lateral-accretion surfaces, channel scours and fills, cross-bedding, graded bedding, reworked sediments and slumping features. These structures are indicative of meandering fluvial deposits (Stone et al., 2002; Stone et al., 2003). This CID also has:

- Fossil wood fragments (haematite-bearing ooid nuclei and larger goethite-rich fragments);
- Clay-filled pods (of both original and secondary origin);
- Various conglomerate facies, e.g., CID intraformational breccia, lithic granule conglomerate and channel-margin layers which are similar to the basal conglomerate; and
- Solution channels and downgrading near channel margins due to clay input from valley sides and weathering or alteration from meteoric water and groundwater.

The unnamed Lower CID sub-unit is 10–30 metres thick and has pervasive alteration of the granules and matrix caused by various iron oxide solution and reprecipitation processes. These have produced a gradational sequence which varies from red-brown haematite- and goethite-bearing CID through yellow-brown ocherous and goethite-rich material with ghost ooid textures to massive and texture-less ochre and brown goethite.

The **Iowa Eastern Member** is the youngest (uppermost) CID unit. It is up to 20 metres thick and consists of the Iowa Eastern Clay and the Iowa Eastern CID. The Iowa Eastern Clay comprises 0–12 metres of locally indurated, mottled white-brown to yellow, kaolinite- and goethite-bearing clay which unconformably overlies the main CID with up to 1.5 metres of matrix supported granule pebble conglomerate at the base. The unit is associated with the Iowa Creek tributary from the north and represents an interruption in CID deposition and/or a change in sediment source. The Iowa Eastern CID sub-unit consists of up to 12 metres of the final phase of CID deposition and is restricted to downstream sections of the palaeovalley.

In the Weeli Wolli tributary palaeovalley CID, the Marillana Formation is unconformably overlain by 10–30 metres of calcrete with interbedded white clay and gravel above the junction with the Marillana Palaeovalley, and poorly sorted gravel over white clay below the junction. The calcrete consists of white–brown, calcareous dolomite and limestone which is locally silicified with chalcedonic silica (Hall and Kneeshaw, 1990). Hall and Kneeshaw (1990) correlated the calcrete, white clay and gravel sequence which overlies the Marillana Formation at Weeli Wolli with the Millstream Dolomite, Kangiangi Clay and Kumina Conglomerate of the western Fortescue Palaeovalley. Macphail and Stone (2004) suggested equivalence of these upper units to the Oakover Formation which has been described as a calcareous lacustrine deposit of Miocene to Quaternary age in the Oakover valley which was eventually drained by headward erosion and capture by the De Grey River system (Williams and Trendall, 1998). Scant lithological similarity or chronological overlap was noted between the Oakover Formation carbonate rocks and the valley calcrete deposits in the nearby Percival Palaeovalley (Williams and Trendall, 1998).

4.6.2.1. Groundwater in the Yandi–Marillana Palaeovalley

The Pilbara is the site of major past, ongoing and future iron-ore mining that requires extraction of significant groundwater resources. This has important implications for the environmental requirements of river-pool systems and groundwater-dependent ecosystems. In 1999, annual groundwater abstraction related to iron-ore mining was 31 x $10^6 m^3$ (from 19 borefields); groundwater was used for mine dewatering, dust suppression, mineral processing and potable town water supply and excess dewatering production was released into modern drainages downstream of each operation. Johnson and Wright (2001) studied the groundwater resources and impact of abstraction from many iron-ore mines in the Central Pilbara. They drew on data from many previous studies, including those undertaken at the BHP and Hamersley Iron operations in the Yandi-Marillana Palaeovalley, and the following discussion relates mainly to that source.

The Yandi-Marillana Palaeovalley aquifers were classified as chemically-deposited aquifers by Johnson and Wright (2001). These groundwater systems consist of CID pisolitic limonite and calcrete deposits, both characterised by extensive secondary permeability and high borehole yields (>1,500 m^3-per-day). CID's are up to 90 metres thick in the Marillana Palaeovalley, forming a highly porous and vuggy heterogeneous aquifer where it occurs below modern drainages incised into basement. Porosity, due to joints and solution cavities, can be up to 25% and near-horizontal clay layers vary in thickness and lateral extent. Groundwater is typically fresh to brackish and bore yields are high (>1,500 m^3-per-day) but delayed yield responses suggest limited interconnection of aquifer pores, possibly due to the presence of clay. The CID aquifer is unconfined with variable transmissivity (200–2,000 m^2-per-day) and groundwater throughflow rates estimated at 2.5–3 x 10^3 m^3-per-day. Localised calcrete aquifers occur near-surface and are typically <10 metres thick, commonly dissected by modern drainage patterns. Calcrete aquifers have secondary karstic solution porosity and recharge is dominated by streamflow leakage with some direct rainfall infiltration. Groundwater in the calcrete deposits is typically fresh and bore yields may be up to 5,000 m^3-per-day, e.g., at Millstream. Palaeovalley aquifers can have hydraulic connection to unconsolidated alluvial aquifers associated with modern drainage systems, and with fractured-rock basement aquifers.

The Marillana Palaeovalley is aligned with the eroded core of the Yandicoogina Syncline and is incised into shale, dolerite and banded iron formations (BIF) of the Weeli Wolli Formation. The easterly flowing Marillana Creek and its associated unconsolidated alluvial aquifer are subparallel to and meander across the Marillana Formation CID aquifer. The unconsolidated alluvial aquifer is 150–400 metres wide and 5–20 metres deep with an estimated throughflow of 5 m^3-per-day. Groundwater recharge and discharge points occur where it crosses the CID aquifer. The Marillana Creek merges with the Yandicoogina and Weeli Wolli creeks prior to passing through the Hamersley Ranges and onto the Fortescue Marshes. The ephemeral Marillana Creek flows only between 30 and 60 days-per-year but provides about 50% of the total water contribution from the Weeli Wooli system to the Fortescue Marshes. Groundwater in the Marillana CID is fresh (<500 mg/L) and thus reduces the overall salinity in the Weeli Wolli CID aquifer. In places where groundwater and surface water seepage from the Weeli Wolli system enters the Fortescue Plain the Fortescue Palaeovalley is at the southern plain margin and brackish groundwater (~5,000 mg/L) occurs. The present Fortescue River drainage system lies at the northern margin of the marsh and groundwater further away from the lateral Weeli Wolli Creek recharge has much higher salinity (up to 70,000 mg/L).

Mining of the Marillana CID currently focuses on sections of the palaeovalley that do not underlie the modern drainage. However, future mining operations may eventually remove much of the CID which coincides with the active river system. Dewatering of the CID aquifer is carried out by a line of permanent bores outside the pit margin and a line of sacrificial bores in the direction of pit extension, which are progressively relocated as the pit expands. In Hamersley Iron–Yandicoogina and BHP–E2 pits the permanent bores are down-gradient of the mine and at BHP–C1 pit they are up-gradient of the mine. As dewatering continues below final mine depth, sumps are developed in the pit floor to drain the less permeable Basal Clay sub-unit at the base of the CID aquifer. In 1999, total dewatering at both Hamersley Iron and BHP operations was $12x10^6$ m^3 from 35 bores, which represents about 50% of licensed allocations. At Yandicoogina the watertable level was stable in early 1999 after initial drawdown in 1998, indicating that the aquifer is near steady-state. The watertable rose later in 1999 following aquifer recharge from substantial rainfall and subsequent streamflow. At the E2 and C1 (BHPB) mines, the watertable level in 1998 was close to the base of the CID aquifer and stable except after recharge due to high rainfall and streamflow. At the E2 mine, flow direction has been reversed (up-gradient towards the mine) for about 5 kilometres downstream and the cone of depression extends about 10 kilometres up-gradient of the mine. Dewatering induces significant watertable drawdown and produces large volumes of excess water, which is returned to the Marillana Creek where it recharges the unconsolidated alluvial and CID aquifers and maintains groundwater throughflow. The aquifer water level is now about 2 metres higher than prior to commencement of dewatering. Modelling suggests that groundwater discharge contributes only 10–15% of the groundwater balance which itself contributes <1% of the combined Weeli Wolli surface and groundwater contribution to the Fortescue Marsh (therefore groundwater discharge has little impact on the ecological water requirements of the marshes).

Mining essentially removes the entire aquifer, resulting in large mine-voids which act as groundwater sinks and commonly form (post-mining) lakes – even with partial backfilling of the voids. The impact of groundwater-filled, mine void lakes is an emerging groundwater management issue in these areas (Commander et al., 1994; Miller et al., 1996; Johnson and Wright, 2001, 2003). The Yandi operations are a good example of a groundwater throughflow mine void (Johnson and Wright, 2001, 2003). The very low overburden to ore ratio (0.2:1) is advantageous for mining but severely limits the amount of available backfill material. Partial backfilling of existing mines is expected to result in a number of shallow elongated voids (Table 4.7).

Table 4.7: Yandi-Marillana CID aquifer iron-ore mine final void dimensions (data from Johnson and Wright, 2001).

MINE	DIMENSIONS (m)	FINAL WATER DEPTH (m)
BHP E2	2,700 x 550 x 45	15
BHP C1/2	4,000 x 550 x 60	17
BHP C5	2,000 x 550 x 60	7
HI Junction (Yandicoogina)	7,750 x 6,000 x 35	Backfill above watertable

The climate is hot, with high evaporation rates (>3,300 mm-per-year) and highly variable rainfall and streamflow. Watertable levels are modelled to recover from significant drawdown induced by dewatering within 15 years post-mining. Total evaporation losses of $10x10^3$ m^3-per-day are suggested for all pit lakes as well as from the Junction Pit where infill will lie above the modelled watertable level and the mine voids will form groundwater sinks. However, infrequent flood events are expected to replenish aquifer levels and maintain adequate CID aquifer throughflow in all but the C5 pit. The salinity at pit C5, which will be dominantly a groundwater sink, will increase from 500 mg/L to 14,000 mg/L in about 250 years. Other pits, which will have at least partial groundwater throughflow, will increase from 1,600 mg/L up to 2,500 mg/L in <100 years. The salinity of groundwater throughflow entering the Weeli Wolli CID aquifer from the Marillana CID is not expected to exceed 2,500 mg/L. Weeli Wolli CID aquifer outflow should reach equilibrium in <100 years and will be monitored to ensure that modelled compliance standards are met, with scope for implementing actions to mitigate adverse environmental effects.

4.6.3. Age and Origin of the Channel-Iron Deposits

Age estimates for the deposition of the palaeovalley fill, and the economically important CID in particular, are based on limited palynology in the basal pre-CID palaeovalley deposits, and from attempted correlation with regional and global climatic and eustatic reconstructions (Morris et al., 1993; Macphail and Stone, 2004; Morris and Ramanaidou, 2007). There is considerable disagreement as to the timing of CID deposition due largely to uncertain correlations of Pilbara region palaeovalley pollen assemblages to sequences with well dated pollen from elsewhere on the continent, thereby resulting in large numerical uncertainties. Balme (in Morris et al. 1993) suggested a Late Oligocene to Middle Miocene age for pollen assemblages in basal units beneath the Robe and Yandi CID. Macphail and Stone (2004) in a detailed study of pollen, including Nothofagus, from the organic-rich dark shale in the Basal Conglomerate of the Munjina Member (Marillana Formation) preferred an Early Oligocene date within possible Late Eocene to Middle Miocene range. Morris and Ramanaidou (2007) reported that other Pilbara pollen assemblages containing Nothofagus were interpreted as Middle to Late Eocene and they suggested that the Nothofagus in samples analysed by Macphail and Stone (2004) were reworked from older deposits during deposition in the Late Oligocene to Middle Miocene. However, in a detailed discussion of their data, Macphail and Stone (2004) rejected contamination by reworked older pollen as an explanation for the Basal Conglomerate pollen assemblage.

There is continued debate as to the genesis of CID (Morris et al., 1993; Stone et al., 2002, 2003; Ramanaidou et al., 2003; Macphail and Stone, 2004; Morris and Ramanaidou, 2007). Both general characteristics and the detailed petrographic character are important for understanding their origins. Important genetic considerations include:

- There is consensus that CID are dominantly channel-bound deposits and have very rarely formed in lacustrine (such as in a blocked channel at Jimmawurrada, Robe deposits) or deltaic environments (such as the lower Fortescue, Robe deposits);

- Their formation requires rare environmental conditions. Morris and Ramanaidou (2007) suggested that the world-wide paucity of CID and their absence from other parts of the Hammersley similar to Robe River and Marillana demonstrated the highly unusual local conditions. However, P. Commander (pers comm., 2007) indicated the likely wider distribution of CID than recognised by Morris and Ramanaidou (2007), based on hydrogeological investigations in the Fortescue valley near Millstream and at Tom Price and Goldsworthy in the Hammersley Range (South Fortescue);
- Remnant rock textures are extremely rare in CID, in contrast to remarkable preservation of such features in detrital iron deposits (DID);
- Pelletoids are extremely common in CID and relatively rare in DID;
- Abundant wood fragments occur, in contrast to the absence of lithic fragments; and
- Granular CID are texturally heterogeneous and, relative to DID and modern fluvial gravels, have a narrow size range of coarse sand to fine gravel (1–5 millimetre diameter).

Detailed petrographic studies (Morris et al., 1993; Ramanaidou et al., 2003; Morris and Ramanaidou, 2007) have established a complex classification of granular CID into:

- **Pelletoids**; including ooids (rounded 0.25–2 millimetre grains complete with nucleus and cortex) and **pisoids** (rounded 2–10 millimetre grains with nucleus and cortex);
- **Peloids** (irregular goethite grains larger than pelletoids and rarely structured),
- **Fossil wood**; and
- **Matrix** material.

Stone et al., (2002; 2003) have disputed the applicability of these CID terms as most grains are typically irregular or sub-angular to sub-rounded. Morris et al. (2007) conceded that the classification is descriptively useful but does not greatly assist understanding their genesis. Morris et al. (2007) also conceded that there is a complete gradational range between:

- Pelletoids and peloids;
- Core, nucleus and cortex within granules;
- Granule cortex and matrix; and
- Wood fragment types.

There is general consensus that the Pilbara palaeovalleys were incised into a landscape established throughout the Palaeozoic and Mesozoic, and that a Cretaceous Pilbara landscape with precursor valleys probably existed. Incision of the palaeovalleys which contain CID occurred in the Palaeogene, probably during the Early to Middle Eocene (Macphail and Stone, 2004; Morris and Ramanaidou, 2007). Macphail and Stone (2004) suggested that the Late Oligocene or Early Eocene age for the Munjina Member Basal Conglomerate indicates that deposition of the overlying Basal Clay, which contains the earliest CID layers, is linked to regional instability associated with the disruption of global climatic and oceanic circulation at the Eocene–Oligocene boundary. Seasonally wet climate regimes following replacement of the cool north-trending eastern boundary current by the warm south-trending proto-Leeuwin current may be associated with CID genesis (Macphail and Stone, 2004). As conditions in north-western Australia became increasingly warmer and probably wetter in the Late Oligocene and Early Miocene, the thicker CID units of the Barimunya and Iowa Eastern Members were deposited. The hiatus or change in sediment source represented by the Eastern Iowa Member Basal Clay is linked to major cooling in the Middle Miocene, and the overlying calcrete is taken as evidence that CID deposition had ceased due to increased aridity in the Late Neogene. Macphail and Stone (2004) recognised two difficulties with their postulated sequence for CID formation. Firstly, there is no direct evidence for CID formation during the very warm wet conditions which existed during the Late Palaeocene–Early Eocene. Secondly, the Munjina Member gradationally abuts the Barimunya Member; this does not accord with a significant depositional hiatus in the Middle Oligocene.

Morris and Ramanaidou (2007) suggested that pollen assemblages containing *Nothofagus* provide evidence for palaeovalley deposition during the Middle to Late Eocene, but that these sediments (red-ochre detritals) preceded CID formation and were followed by a long hiatus which resulted in a haematite-dominated hardcap. Deposition of Oligocene to Miocene conglomerate and clay deposits with lignite (Munjina Member and equivalents) was followed by deep chemical weathering under warm conditions in the Early to Middle Miocene. This weathering event formed a thick and widespread ferrisol over all rock types, and was the source material for the CID. Uplift and rejuvenation during the Middle Miocene resulted in stripping of the ferrisol landscape to form the CID, in a relatively short period which was probably characterised by recurring cycles of wet to arid climate that induced multiple burial, ferruginisation and re-exposure events. Widespread sediment stripping culminated in the Late Miocene with increasing cold, aridity conditions and deposition of calcrete deposits which are equivalent to the Oakover Formation. The textural and petrological complexity of the CID reflects both the highly variable conditions during ferrisol stripping and CID deposition as well as the complex post depositional diagenetic and pedogenic processes which have occurred due to movement of groundwater and meteoric water through the CID (Morris and Ramanaidou, 2007).

The abundance of wood fragments and charcoal in the CID implies that abundant vegetation occurred in the CID source areas (Macphail and Stone, 2004; Morris and Ramanaidou, 2007). This vegetation and/or fire events may have played a significant role in generation and transport of the CID.

4.6.4. De Grey Palaeovalley

Davidson (1975) reported on groundwater investigations in the north-west Pilbara in 1969–1972 which aimed to augment water supplies for Port Hedland. Following an initial survey of waterbores the study focused on the lower De Grey River at its confluence with the Strelley and Shaw river tributaries at the northern edge of the Pilbara Block, about 100 kilometres west of Port Hedland. Davidson (1975) identified a number of bedrock and alluvial aquifers but focused on palaeovalley sediments with 49 levelled investigation bores sited on the basis of geophysical data (seismic and resistivity surveys) designed to delineate the palaeovalley location. Bores were drilled through the palaeovalley fill to weathered bedrock. However, despite the focus on palaeovalley aquifers, scant details are provided about the palaeovalley or the composition of its sediment profile. The area of investigation included the De Grey Palaeovalley (in the vicinity of the junction of the Shaw and De Grey rivers), shown by drilling to be about five kilometres wide, 33 kilometres long, and up to 75 metres deep. Bores and cross-sections also examined the lower valley reaches of the Shaw and Strelley drainage systems.

The modern De Grey River channel lies at the north-east margin of the De Grey Palaeovalley, upstream of the Shaw and south-east of the channel downstream of the Shaw. The palaeovalley sediment infill is divided into an upper and lower unit. The lower sandy unit occurs as thin beds and lenses with rare gravel beds; these vary in thickness and permeability and have more clay in the Shaw and Strelley Palaeovalley than in the De Grey. The upper sand unit consists of coarse-grained sand and gravel, commonly with calcrete deposits formed at the watertable. The lower and upper sand units may be separated by silty clay, although sediment units are mostly hydraulically connected in the De Grey Palaeovalley.

4.6.4.1. Groundwater in the De Grey Palaeovalley

Davidson (1975) demonstrated that a significant sustainable groundwater resource occurs in the De Grey Palaeovalley. Groundwater recharge of the De Grey Palaeovalley is dominated by river flow even though it is highly intermittent. Chloride ratios suggest that about 3% of rainfall reaches the watertable as direct recharge through the alluvium which equates to 1.4 x 10^6 m^3-per-year over the 170 square kilometres of the palaeovalley study area. This is equivalent to about 8% of the total aquifer recharge, calculated to be 17 x 10^6 m^3-per-year (Davidson, 1975). Recharge is balanced by 13.75 x 10^6 m^3-per-year transpiration from river bank vegetation, 0.65 x 10^6 m^3-per-year evaporation from river pools and 2.2 x 10^6 m^3-per-year groundwater outflow. The groundwater storage was estimated by Davidson (1975) to be 82 x 10^6 m^3 (including 17 x 10^6 m^3 annual recharge) with 60% of potable salinity (300–1,000 mg/L TDS) and 40% with salinity (1,000–2,000 mg/L TDS). Davidson (1975) estimated a minimum safe yield of 7,600 m^3-per-year which did not take account of any reduction of transpiration loss or enhancement of recharge which might be induced by lowering the watertable.

4.6.5. Fortescue-Robe Palaeovalley Continuation on the Coastal Plain

Commander (1994a; 1994b) examined the stratigraphic sequences and groundwater resources of the Quaternary alluvial aquifers of the Robe and Fortescue River systems on the coastal Ashburton Plain, downstream of their debouchment from the Pilbara bedrock terrane. The sequence recognised from drilling included extensions of the palaeovalley sediment deposits. The Robe River area represents the original course of the Fortescue Palaeovalley prior to capture from the north-west by the modern Fortescue course (Barnett, 1981), and the Robe Formation CID palaeovalley sediments are known to extend into the subsurface of the coastal plain (Williams, 1968). Up to 30 metres of Cenozoic sediments in the Robe River coastal plain overlie Cretaceous rocks of the Carnarvon Basin and the Proterozoic sequence of the Ashburton Basin. Cretaceous sedimentary rocks include the fluvial Yarraloola Conglomerate, recognised from basal channels underlying the Fortescue Palaeovalley sequence further upstream (Barnett and Commander, 1985). Commander (1994a) reported subsurface Robe Formation on both sides of the present river channel. The formation includes up to 7 metres of red-brown and black pisolitic ironstone, yellow clay and red–yellow silcrete. The fluvial Robe Formation was probably deposited in the Late Eocene and has been weathered and subjected to secondary iron and silica precipitation in the Oligocene (Commander, 1994a). The Trealla Limestone occurs over much of the coastal plain, unconformably overlying older Cretaceous or Tertiary sediments. In the Robe River area it consists of up to 17 metres of crystalline limestone with pale cream and yellow clay. The Trealla Limestone is similar to the Millstream Dolomite and has a similar stratigraphic relationship to the Robe Formation. It is believed to be a Mid Miocene marine or lagoonal equivalent to the Millstream Dolomite. Cenozoic sediments up to 50 metres thick in the Fortescue River area also overlie Cretaceous and Proterozoic rocks. The Yarraloola Conglomerate infills a basal channel and is either variably overlain by Cretaceous marine shale or is unconformable with the Mid Miocene Trealla Limestone. Robe Formation palaeovalley sediments are not present in the subsurface of the Fortescue River area of the coastal plain. Up to 30 metres of Quaternary alluvial sediments overlie the Trealla Limestone in the coastal plain of the Robe and Fortescue rivers, typically forming alluvial fans adjacent to the river debouchments.

Quaternary alluvium is the main aquifer system on the coastal plain (Commander, 1994a; 1994b). The channel-filling Yarraloola Conglomerate forms an aquifer of restricted distribution, confined by overlying Cretaceous shale or Cenozoic Trealla Limestone. Abundant clay within the limestone unit means that it rarely forms an aquifer, except where limestone is fissured and in continuity with Quaternary alluvium. Commander (1994a) failed to comment on the aquifer potential of the Robe Formation in the Robe River area of the coastal plain. Recharge of all coastal plain aquifers is dominated by direct infiltration to the alluvium from the river bed during surface flow and also from the alluvium to other aquifers. The occurrence or potential for lateral throughflow from palaeovalley aquifers in the Robe–Fortescue river system to coastal plain aquifers was also not covered in detail by Commander (1994a; 1994b).

4.7. MURCHISON AND GASCOYNE RIVERS REGION

The Murchison–Gascoyne region lies south of the Pilbara (Figure 4.26) and extends across a variety of Precambrian terranes including Proterozoic igneous and metamorphic rocks of the Gascoyne Province, Proterozoic sedimentary rocks of the Bangemall Basin and discontinuous Archaean greenstone belts and granitic intrusions of the Murchison Province (Yilgarn Craton). Similar to the main Pilbara drainages further north, the Murchison and Gascoyne rivers are large, highly variable ephemeral drainage systems which cover broad catchments, e.g., the catchment area of the Murchison River is 91,254 square kilometres and the catchment of the Gascoyne River is 75,835 square kilometres. These catchments trend westerly across the interior basement terranes and Carnarvon Basin sediments along the Indian Ocean coastal plain. The climate is hot, semi-arid to arid with highly variable mostly summer-dominant rainfall, generally derived from cyclones and thunderstorms, although winter low-pressure frontal rains also occur.

Palaeovalleys in the Murchison–Gascoyne are known to occur (e.g., Johnson and Commander, 2006) but their distribution, character and groundwater resources are virtually unknown. The detailed state-wide palaeodrainage maps of Beard (1973) and van der Graaff et al. (1977) did not encompass areas with active drainage systems such as the South Coast, Kimberley, Pilbara and Murchison. In general, the lack of recognition of palaeovalley systems within or underlying presently active drainages continues to be an oversight in palaeodrainage reconstructions. Palaeovalleys in the Murchison–Gascoyne region probably share characteristics with other parts of the Yilgarn and the Pilbara. For example, both CID (Ramanaidou et al., 2003) and calcrete deposits (Laws, 1992; Johnson and Commander, 2006) are known to occur. Similar to the Pilbara, large floods in the ephemeral rivers inundate the typically extensive valley floors, including near-surface palaeovalleys and enhanced recharge may subsequently occur from surface runoff. Similarly, leakage from perennial surface river flow may also contribute significant recharge to groundwater resources on the coastal plains where groundwater connectivity exists between the palaeovalley and coastal plain aquifers.

Palaeovalley calcrete aquifers in the Wiluna area, just east of the Murchison catchment, have been extensively exploited for domestic, pastoral and horticultural use (Sanders, 1972, 1974). Early hydrogeologic assessment of calcrete resources included similar calcrete deposits in the nearby upper Murchison catchment further west (Sanders, 1969; Sanders and Harley, 1971). Older (Morgan, 1965, 1966) and more recent (Laws, 1992; Johnson and Commander, 2006) hydrogeological surveys have covered much of the Murchison but provided limited information on palaeovalley characteristics or groundwater resources. A number of mining towns including Meekatharra, Mt Magnet and Cue use groundwater for town supplies within the Murchison catchment. Baxter (1967) has discussed aspects of the hydrogeology of the Gascoyne River coastal plain but no studies of the bedrock part of the catchment (which are most likely to have palaeovalleys) have been located during this review, and the Gascoyne portion of the region is thus very poorly known.

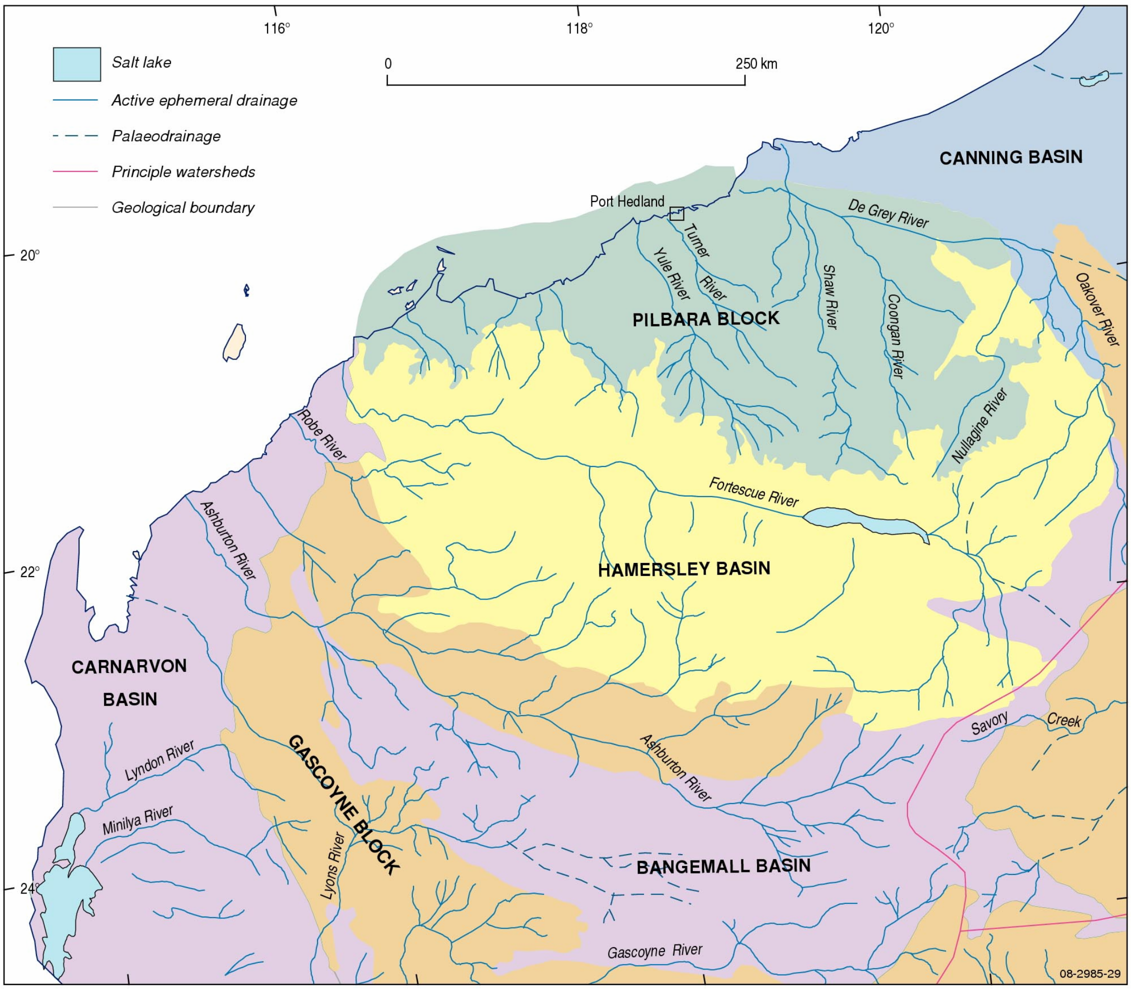


Figure 4.26: *Location map of the major geologic terranes in north-west Australia, which include the Murchison–Gascoyne region.*

The regional assessment of the hydrogeology of the Murchison catchment by Laws (1992) recognised that alluvial and calcrete aquifers are associated with ancient drainage patterns but did not recognise or describe palaeovalley fill sequences or palaeochannel sand aquifers. Johnson and Commander (2006), in the most recent review of the hydrogeology of the region, have recognised three aquifers associated with the palaeodrainage system including Quaternary surface alluvium, Palaeogene calcrete and Neogene palaeochannel sands. Quaternary alluvial aquifers comprise 5–20 metres of fine- to coarse-grained quartz sand with lenses of gravelly silt and clay which interfinger with colluvium derived from laterally adjacent bedrock slopes. Calcrete is formed in the palaeodrainage network by in situ replacement of palaeovalley sediments, due to phreatic precipitation of magnesium and calcium carbonate from carbonate-saturated groundwater (Mann and Horwitz, 1979). Calcrete is common adjacent to playas and in trunk palaeovalleys in the upper Murchison catchment and to the east and north, but is sparse towards the south (Sanders, 1969; Sanders and Harley, 1971). Palaeovalley calcrete zones are generally <10 metres thick and commonly have karstic weathering, well developed secondary solution porosity and high permeability. Palaeochannel aquifers are poorly understood in the region, although Johnson and Commander (2006) suggested they are likely similar to those of adjacent Yilgarn palaeovalley sequences such as the Carey and Raeside Palaeovalleys (Johnson et al., 1999). Palaeochannel aquifers just south of the region (northern Moore–Monger River catchment) have been investigated and exploited for mine processing supplies at Mount Gibson and Windimurra (Section 4.8.3). These studies have suggested 10–40 metres of basal coarse- to fine-grained carbonaceous fluvial sand is confined by up to 40 metres of dense kaolinitic clay. Palaeovalley sequences in the Murchison may well be similar.

4.7.1. Murchison and Gascoyne Region Groundwater

Similar to the stratigraphic and sedimentologic characteristics of palaeovalleys in the Murchison and Gascoyne region, palaeovalley groundwater resources here are poorly known (Johnson and Commander, 2006). Quaternary alluvial aquifers are under-utilised in the region (Johnson and Commander, 2006) compared to the Northern Goldfields (Johnson et al., 1999) where they are a significant source of relatively low-salinity groundwater. Town water supplies for Cue, Meekatharra and Mount Magnet are mostly obtained from calcrete aquifers. Bore yields are variable, up to 100 m^3-per-day, and groundwater salinity varies from potable (Mount Magnet town supplies) to saline (>7,000 mg/L TDS) in some lower palaeovalley reaches. Johnson and Commander (2006) suggested that use of the Quaternary alluvial aquifer is limited by low permeability, although groundwater probably leaks to more permeable underlying aquifers. Calcrete generally forms an excellent aquifer with bore yields of >1,000 m^3-per-day, although groundwater is mostly brackish with TDS of 2,000–6,000 mg/L; this reflects the location of most calcrete zones in lower palaeovalley reaches. Calcrete aquifers which receive relatively high recharge rates from runoff, and which occur above the local groundwater drainage base-level, may contain potable supplies. Such groundwater resources are used for town-water supplies at Meekatharra and Cue. Palaeochannel aquifer bore yields at Mount Gibson are 100–1,000 m^3-per-day, increasing down-gradient, although groundwater is saline to very saline, e.g., 30,000–100,000 mg/L TDS. Broad-scale groundwater resource studies in the region are cited by Johnson and Commander (2006) but these were not based on detailed aquifer investigation and are believed indicative only.

The borefields at Meekatharra and Cue occur in an area where other bores are used to supply groundwater for mine processing. Borefields are typically separated by at least 50 kilometres and there is no evidence of inter-field interference. Johnson and Commander (2006) inferred that most potable groundwater resources to the east of the coastal aquifers contain relatively high nitrate levels (> 45 mg/L). Calcrete aquifers near Wiluna have provided high yields (>4,500 m^3-per-day during peak gold mining activity) of potable groundwater which has supported citrus orchard and vineyard horticultural operations. However, Johnson and Commander (2006) suggested that relatively elevated salinity levels in the higher yielding calcrete aquifers would restrict horticultural operations to fodder crops, such as lucerne, which can tolerate water with up to 3,000 mg/L TDS. The mining industry is the largest groundwater user in the region; demand increased from 0.6×10^6 m^3-per-year in 1983 to 25.3×10^6 m^3-per-year in 1994, with water obtained from pits, shafts and borefields and variously used for dust suppression, ore processing and potable camp supplies (Johnson and Commander, 2006). Abstraction was reduced in 1996–1997 due to decommissioning of some operations and switching of mine-processing water sources from borefields to dewatering operations. Cumulative groundwater abstraction over the period 1983–1997 was estimated at 165×10^6 m^3-per-year by Johnson and Commander (2006) who suggested that, in 1996, about 40% of total allocation (66.9×10^6 m^3-per-year) was actually used. Newer gold ore processing techniques (e.g., CIP – carbon-in-pulp) allow the use of highly saline water but with increased reagent costs. Unlike most mining operations in the Northern and Eastern Goldfields, where saline palaeochannel groundwater is commonly used, mining operations in the Murchison Province use groundwater mostly drawn from fractured-rock aquifers, much of it sourced from dewatering operations.

4.8. WESTERN YILGARN (SOUTH–WEST DRAINAGE DIVISION)

The Yilgarn Craton is the largest and oldest geologic terrane in Western Australia and one of the oldest continuously exposed portions of continental crust on Earth (Figure 4.27). It comprises north-

north-west trending belts of highly metamorphosed and deformed greenstone rocks (i.e., Archaean sedimentary and felsic, mafic, and ultramafic intrusive and volcanic rocks) within larger areas of more weakly metamorphosed and deformed Archaean granite. The Yilgarn is bounded to the east and west by Phanerozoic sedimentary basins and to the north and south by metamorphosed Proterozoic orogenic terranes. The Yilgarn Craton forms a low relief plateau from 200–600 metres AHD. The region formed a large and tectonically stable continental peninsula which was connected to Antarctica in the Mesozoic. During this mega-continent stage, the region had a north–south central watershed (Beard, 1973, 1998), which developed coevally with the Mesozoic primary palaeovalley system described by de Broekert and Sandiford (2005). The portion of the western Yilgarn characterised by palaeovalleys corresponds to the South-West Drainage Division of Mulcahy and Bettenay (1972). West-trending drainage divisions further north on the western Yilgarn and Pilbara Cratons (Murchison and Pilbara drainage divisions) have associated existing coherent active river systems, such as the Murchison, Gascoyne, Ashburton, Fortescue and De Grey rivers.

Detailed soil mapping in the South-West Drainage Division (Mulcahy and Hingston, 1961; Bettenay and Hingston, 1964) recognised that the palaeovalleys contain thin and extensive sediment sequences which are relatively unweathered. These overlie more deeply weathered pallid zones and were originally interpreted as valley fill sediments formed coevally with the deeply weathered landscape, rather than with its dissection. Subsequently, Mulcahy (1967) defined the Meckering Line, where the downstream portion of the valleys change to more incised valley forms, indicating the extent of drainage rejuvenation. The Meckering Line extends from beyond Moora in the north through Meckering and beyond Wagin in the south. East of the Meckering Line, within the palaeodrainage zone, Beard (1999) recognised an approximate northerly trending median drainage divide with the west-trending drainage to the east focused through a single gap in the divide, the Caroline Gap, and connected to the Avon–Swan River system. Beard (1999) and Commander et al. (2001) both indicated that the median divide is of considerable antiquity and rivers to the east formerly flowed south towards a seaway opened between Australia and Antarctica in the Jurassic, before rifting caused disruption and diversion. The major divides which separate palaeovalleys and palaeodrainage divisions in the interior tend to be undulating uplands, with ferricrete and sandplain landscapes, rather than mountain ranges (Mulcahy and Bettenay, 1972; Beard, 1973). The South-West drainage division includes a number of short, seasonally active stream channels west of the Meckering Line. These include the Blackwood, Collie, Murray, Avon–Swan, Moore and Arrowsmith rivers; each of these have (or previously had) connection to palaeovalleys east of the Meckering Line, although the ancient drainage connections are now commonly disrupted or diverted by uplift of the Darling Range. De Broekert's (2003) study of regolith and landscape in the upper catchment of the Murray River west of the Meckering Line suggested that Palaeogene palaeovalleys are absent due to erosion and rejuvenation. Clarke (2005) suggested that Eocene fluvial deposits in these areas form interfluves due to relief inversion. However, the Blackwood, Avon–Swan, and Moore–Monger systems have major palaeovalley connections across the Meckering Line (as discussed in further detail below).

Palaeovalley evolution in Western Australia's Wheatbelt region, which occupies much of the western part of the Yilgarn, has been well documented by George et al. (2006). Salinisation was manifest in the Wheatbelt from 2.8 million years ago (Ma), with saline zones concentrated along valley floors as cyclic climate systems (arid and wetter cycles) prevailed. Agricultural development subsequently altered the water balance on 20 million hectares of cleared farmland, exacerbating degradation of 300,000 hectares of variably saline land that existed before the arrival of Europeans, and spreading across an additional 1.1 million hectares of formerly non-saline land, including unique habitats and ecosystems.

Figure 4.27: *Map of the Western Yilgarn Block showing the network of active rivers, palaeodrainage systems and salt lakes identified across south-western WA. Sediments of the Perth Basin and Carnarvon Basin extend onshore (shown in yellow) and abut the western edge of the Yilgarn Craton. Figure is modified from Beard (1973).*

Groundwater in the western Yilgarn is contained in three aquifer systems:

- Weathered and fractured Archaean bedrock;
- Basal palaeochannel sands; and
- Overlying Late Neogene alluvial/colluvial and aeolian sediments which commonly cap the palaeovalleys.

4.8.1. Blackwood River Catchment Palaeovalleys

The Blackwood River (Beard, 1999) is perennial and occupies a sinuous course in a narrow valley (20–40 kilometres wide) from its mouth at Augusta to where it widens at the junction of two ephemeral major tributaries, the Arthur and Beaufort rivers. Both of these tributaries follow or comprise palaeodrainage features, particularly the Beaufort River (Figure 4.28). The Beaufort system has two palaeovalley tributaries, the Coblinine River and Dongolocking Creek; these form conspicuous north- and south-trending zones in the eastern catchment where rainfall, relief and gradients are all low. The combined Coblinine–Dongolocking Palaeovalley enters a tract containing a number of lakes, playas and salt flats including Lake Dumbleyung a large permanent salt lake which was reported inconsistently as a dry lake (Beard, 1999) and permanent saline lake (Beard, 1980) at European contact. The consensus in many other published hydrogeological summaries suggests that Dumbleyung was brackish at first contact and has progressively become significantly salinised. Irrespective of the true state of Lake Dumbleyung at first-contact, there is little doubt that agricultural clearing has raised the watertable and contributed to salinisation across much of the lower salt flat and playa of this palaeodrainage.

Eocene sediments occur in the Beaufort Palaeovalley and other west-draining palaeovalleys further south (Waterhouse et al., 1995; Commander et al., 2001). The valleys are broad (5–15 kilometres-wide) with flattened bases and very low gradients. Salt lakes are also common. The Beaufort Palaeovalley is situated west of the Meckering Line and has a predominantly westerly trend which indicates that it was formerly connected to a drainage system further west, e.g., through the Preston or Collie rivers. It has subsequently been captured by the more south-west trending Blackwood River. The palaeovalley was traced by Waterhouse et al. (1995) some 60 kilometres in a different orientation to the modern drainage, sporadically crossing the palaeovalley course.

The Beaufort Palaeovalley fill is commonly 60–70 metres thick and divided into two units. The lower unit consists of interbedded, dark brown and grey, carbonaceous, rounded to sub-rounded sand, clayey sand and clay which occurs in a relatively narrow (200–500 metre) channel directly overlying weathered Archaean bedrock. Deposition is interpreted to have occurred in a wide range of localised environments within a meandering river system. The upper unit is pale grey to white, dominantly clay and silt with minor sand and generally extends over a wider area than the lower unit, commonly onto palaeovalley flanks. However, it is not present across the entire Beaufort Palaeovalley. This unit was deposited in more widespread lacustrine conditions, probably in response to decreased surface gradients due to further uplift in the west. Waterhouse et al. (1995) reported well preserved pollen assemblages, clearly of Middle to Upper Eocene age throughout most valley fill sequences. Commander et al. (2001) asserted unequivocally that sedimentation did not occur in the palaeovalley during the Late Oligocene to Mid Miocene, and that this was a period when the palaeovalley fill underwent deep weathering and ferricrete development. Waterhouse et al. (1995) reported a sparsely distributed second cycle of fluvial sand overlain by clay above the main palaeovalley units in the Towerrinning area of the Beaufort Palaeovalley. The angular sands of the upper sequence suggest local derivation and minimal valley transport. These may be equivalent to Late Miocene–Pliocene Wheatbelt palaeovalley sediments reported by Commander et al. (2001)

from a number of sites and believed to be widespread in the Yilgarn–Salt River Palaeovalley just to the north (Salama, 1994; 1997).

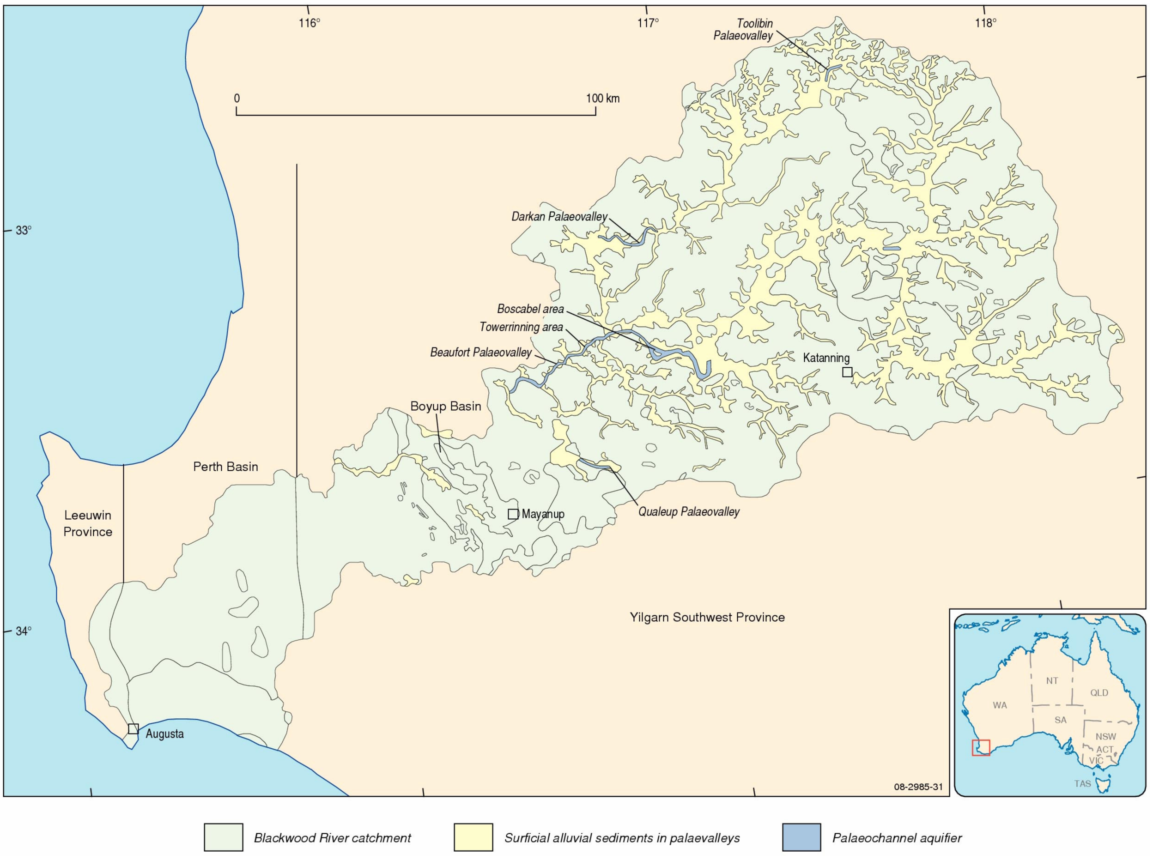


Figure 4.28: *Map of the Blackwood River catchment in the South-West Drainage Division, showing the spatial distribution of Cenozoic alluvial sediments in palaeovalleys and the main palaeovalley aquifers. Figure is modified from De Silva et al. (2000) (Figure 7).*

4.8.1.1. Blackwood Catchment Palaeovalley Groundwater

The palaeovalleys and groundwater resources of the upper part of the Blackwood River catchment were investigated by De Silva et al. (2000). Deeply weathered bedrock profiles in this part of the south-west Yilgarn are characterised by variable, but predominantly low, porosity and hydraulic conductivity levels; faults, fractures and joints are commonly localised and have limited groundwater resource potential. Thus, fractured and weathered bedrock aquifers are not associated with substantial groundwater supplies in this part of the Blackwood River catchment. The quality and quantity of groundwater resources in the surficial and palaeochannel aquifers depend mainly on variables influenced by landscape position, for example, the thickness and lateral extent of sediment sequences with elevated hydraulic conductivity values (porous sand and gravel horizons), the hydraulic connection of such materials to recharge sources and the quantity of groundwater recharge and throughflow (De Silva et al., 2000).

Basal palaeochannel sand units (average width ~ 1 kilometre) extend from 8–50 kilometres in broad palaeovalleys in the upper-middle and upper portions of the Blackwood River catchment, commonly covered by younger Cenozoic sediments. These sand horizons form minor and major unconfined to semi-confined aquifers, depending on the continuity of hydrological connection. High bore yields are restricted to sandier zones with minimal clay content and more clay-rich sediments are characterised by lower yields and higher salinities. Generally, highly saline palaeochannel groundwater (especially at palaeochannel margins) is associated with poor drainage in the lower landscape, and with high salinity recharge from both overlying surficial aquifers and lateral weathered bedrock aquifers. Fresh to brackish groundwater occurs in sandier central sections of palaeochannel aquifers where major recharge is from rapid aquifer throughflow derived from fresher upstream sections or from direct rainfall recharge (where unconfined).

The Toolibin Palaeochannel, in the north-east Blackwood River catchment, forms a locally important aquifer which initially proved difficult to discriminate from weathered bedrock – experience from drilling palaeovalley sequences elsewhere in the Yilgarn was needed to define this aquifer (De Silva et al.., 2000). Drilling showed that the palaeovalley is at least 6 kilometres long and trends south-west beneath Lake Toolibin. The sediment infill consists of 35 metres of layered sand, clay and carbonaceous clay which is interpreted to be of Late Miocene to Pliocene age. The palaeochannel aquifer is confined to semi-confined by a clay-rich layer up to 10 metres thick. Extractable groundwater occurs in the various sand layers at yields ranging from 12–300 m^3-per-day (Dogramici, 1999), with salinity from 3,400–3,600 mg/L TDS (De Silva, 1999). Lake Toolibin and surrounding reserves are important breeding habitats for birdlife and are Ramsar-listed wetlands. The lake is affected by dryland salinity which is characteristic of valley floors in the cleared landscapes of West Australia's Wheatbelt. Salinity of the lake increased due to rising salinity of the North Arthur River which drains 90% of the catchment. Investigations into rising salinity of Lake Toolibin and its consequent deterioration as a wetland conservation reserve began in 1978 (NARWAC, 1978) and continue to the present-day, with varying management strategies implemented since 1982 (Martin, 1982). Irrespective of their success in rehabilitating Lake Toolibin, the large number of studies has provided information on the characteristics and connectivity of surface water and groundwater at a local-scale in this south-west Yilgarn palaeovalley (Dogramici et al., 2003). The Toolibin palaeochannel aquifer is highly transmissive and consists of 20–30 metres of sub-angular to sub-rounded, fine quartz sands. These were deposited within the original alluvial channel and are indicative of relatively short transport distance and rapid deposition. At Lake Toolibin the palaeochannel width is unknown as it is overlain by up to 8 metres of fine-grained lacustrine clay that extends beyond the present extent of the lake and surrounding lunettes.

The Qualeup Palaeovalley occurs near Qualeup in the upper-middle Blackwood River catchment and is at least 10 kilometres long. The palaeovalley infill sequence consists of up to 25 metres of sediment (thick), including about nine metres of palaeochannel sand. The palaeochannel sand aquifer is unconfined or semi-confined by overlying low-permeability sediments, as indicated by the standing water level in bores. The maximum extractable groundwater yield is 200 m^3-per-day, with groundwater salinity from 3,500–4,500 mg/L (De Silva et al., 2000).

The Beaufort Palaeovalley, also situated in the upper-middle Blackwood River catchment, is the largest local palaeodrainage system. It consists of a sinuous network of over 60 kilometres of mostly westerly trending palaeovalleys. Near Boscabel, at the eastern end of the palaeovalley, the sedimentary sequence consists of fluvial and lacustrine sand, silt and clay up to 55 metres thick. The palaeochannel sand aquifer has up to 26 metres of upward-fining sand and gravel units. An overlying clay sequence of variable thickness (up to 20 metres) causes both confined and unconfined groundwater systems in the palaeovalleys, with the standing water level 1–8 metres below ground-level. A topographic divide in the Boscabel area, presumably developed post-palaeovalley formation, results in both eastward (towards Beaufort Flats) and westward (towards the Beaufort River) groundwater flow. Extractable groundwater yield estimates range from 40–280 m^3-per-day, with no apparent correlation between thickness of the sand aquifers and groundwater yield. Groundwater salinity ranges widely from 1,000–7,500 mg/L and generally increases with depth, suggesting some degree of density stratification (De Silva et al., 2000). In the Towerrinning area, in the central reaches of the Beaufort Palaeovalley, the sedimentary infill is up to 39 metres thick. The main palaeochannel aquifer here consists of up to 28 metres of upward-fining sand. A topographic divide also occurs downstream of Towerrinning, with groundwater flow directed eastwards and westwards. Groundwater systems in this region are both confined and unconfined, with the highest groundwater flow rates in the confined aquifers (bore rates of >100 m^3-per-day). Extractable groundwater yield estimates are highly variable in this area, ranging from 12–187 m^3-per-day, also with no apparent correlation between aquifer thickness and groundwater yield. Groundwater salinity in the Towerrinning region is variable (340–8,700 mg/L) and tends to increase with depth, with fresh groundwater restricted to localised pockets or lenses where local recharge occurs on the sub-catchment scale (De Silva et al., 2000).

The Darkan Palaeovalley occurs near the boundary between the lower-middle and upper-middle parts of the Blackwood River catchment. This is a sinuous 20 kilometre-long palaeovalley which trends westerly towards the Cenozoic Dardadine sub-basin. The palaeovalley sediments occur in a 500 metre-wide channel section and are 30–45 metres thick in the main sand aquifer. Groundwater salinity is about 450 mg/L. The groundwater resource contained within the main palaeovalley aquifer is about 30 x 10^6 m^3, although lower groundwater yields and higher salinity levels probably occur near the palaeochannel margins as the aquifer is relatively thinner and finer, and lateral groundwater inflow from weathered bedrock occurs (De Silva et al., 2000). About 10 kilometres to the west, a bore transect across the Hillman River valley intersected up to 23 metres of mixed sand- and clay-rich palaeovalley sediments overlain by up to 5 metres of Quaternary cover sediments. This unconfined to semi-confined palaeochannel sand aquifer yielded 230–302 m^3-per-day decreasing from the valley centre towards the edge of the palaeochannel. The groundwater salinity at Hillman River ranges from 5,600 mg/L in the centre of the palaeochannel up to 26,000 mg/L at the margins (De Silva et al., 2000).

Surficial aquifers are generally unconfined and comprise heterogeneous Quaternary fluvial sediments in modern drainages and alluvial or colluvial sand, silt, clay, gravel and ferricrete in the broad palaeovalleys, which overlie weathered bedrock and older palaeovalley infill. Little quantitative information on the groundwater characteristics of the surficial aquifers or their connectivity with underlying palaeovalley aquifers is currently available.

4.8.2. Yilgarn River–Salt River Palaeodrainage

The complex Yilgarn River–Salt River palaeodrainage has multiple drainage disruptions and diversions of varied age and now drains westwards via the Caroline Gap, connecting to the modern Avon–Swan River system (Figure 4.29). The history of drainage disruption and diversion, and evolution of the palaeovalley shape, course and sediment infill, have been extensively studied, e.g., Beard (1999), Salama (1994, 1997), Salama et al. (1992, 1993). The Yilgarn River palaeodrainage forms a complex pattern which covers the entire medial and central watersheds in the South-West Drainage Division (Beard, 1998, 1999). Former south-flowing Mesozoic rivers were diverted in the Cenozoic and now join the Yilgarn River system, exiting through the median watershed at Caroline Gap and continuing south-west via the Salt River to form the Yenyenning Lakes prior to joining with the Avon River. The Yilgarn River–Salt River palaeodrainage was probably active during the Eocene, flowing westward to the present Swan River mouth. Salama (1994) attributed formation of the Kings Park Formation in the Eocene to deposition by the Yilgarn River prior to uplift along the Darling Fault escarpment. However, Eocene sediments have not been identified in the Yilgarn–Salt River palaeovalleys (Salama, 1997). Following post-Eocene uplift of the Darling Ranges the

Yilgarn–Salt River system was defeated and dammed, forming a large lake (Yilgarn Lake) where the Yenyenning Lakes now occur. Subsequently, the present north-westerly course of the Avon River was captured, draining the Yilgarn–Salt River system.

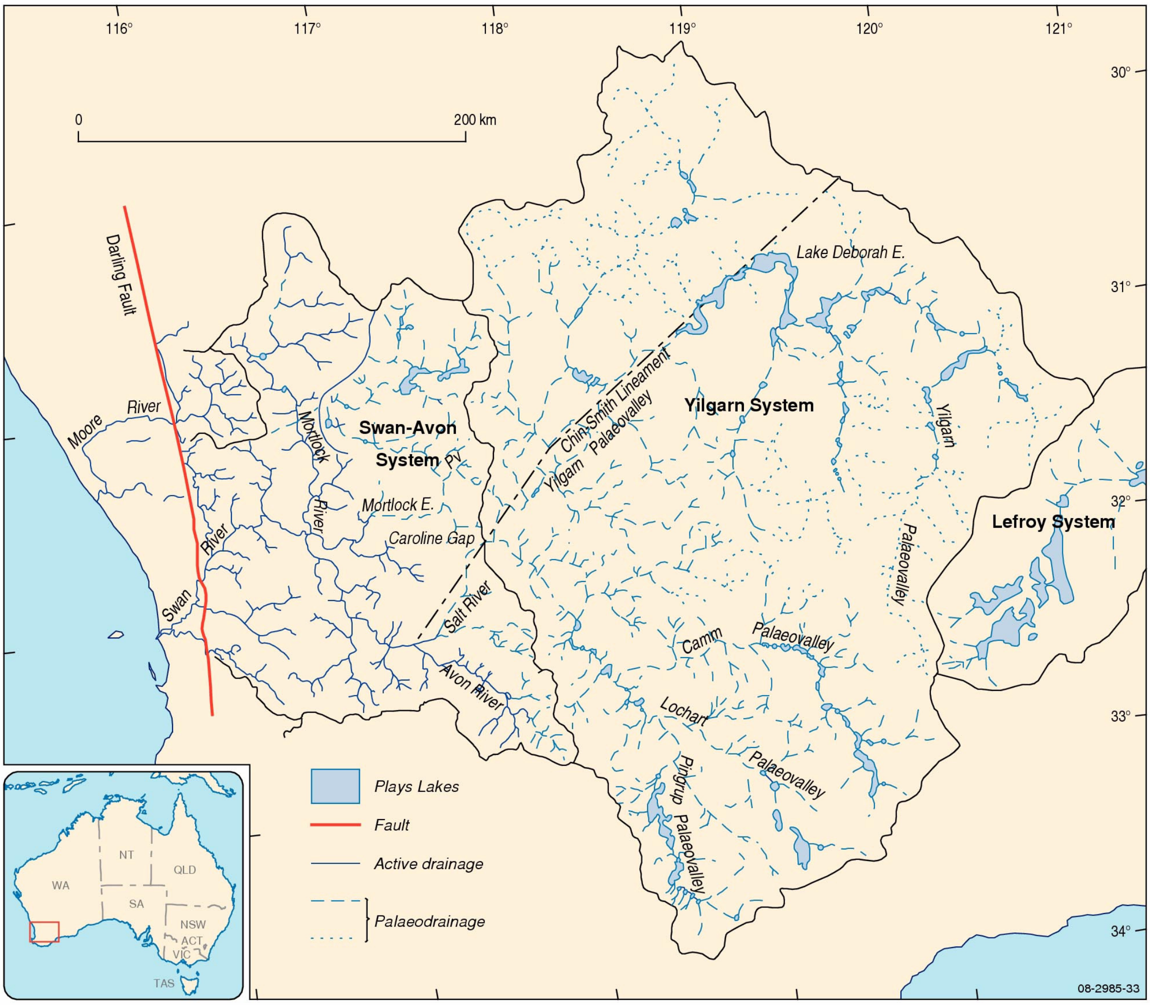


Figure 4.29: *Map of palaeodrainage distribution in the Yilgarn River–Salt River system. Note how the palaeodrainages of the Yilgarn region join with the perennial and ephemeral drainages of the Swan–Avon Catchment. Connected chains of multiple salt lakes in the Yilgarn define the palaeodrainage system in many places. Figure is modified from Beard (1999) (Figure 1).*

Salama (1997) reported on drilling of the Salt River Palaeovalley sequence, which identified three sedimentary units with a variable thickness of 30–70 metres (Figure 4.30). The deepest unit, the Quairading Sandstone, consists of multi-coloured, fine- to coarse-grained sands which are sub-rounded to well-rounded and cemented in a clay matrix. The Quairading Sandstone is commonly cross-bedded and was probably deposited in a high-energy fluvial environment. The sandstone sequence does not outcrop and, because of uncertain stratigraphic position and relationship with other units, its age is unknown, although Salama (1997) suggested that it formed in the Oligo–Miocene. The second unit, the Yenyenning Formation, is also only known from drilling, i.e., it does not outcrop. These sediments consist of green to grey clay and sandy clay, with inter-layered black mudstone and organic deposits which contain fossilised leaves and branches.

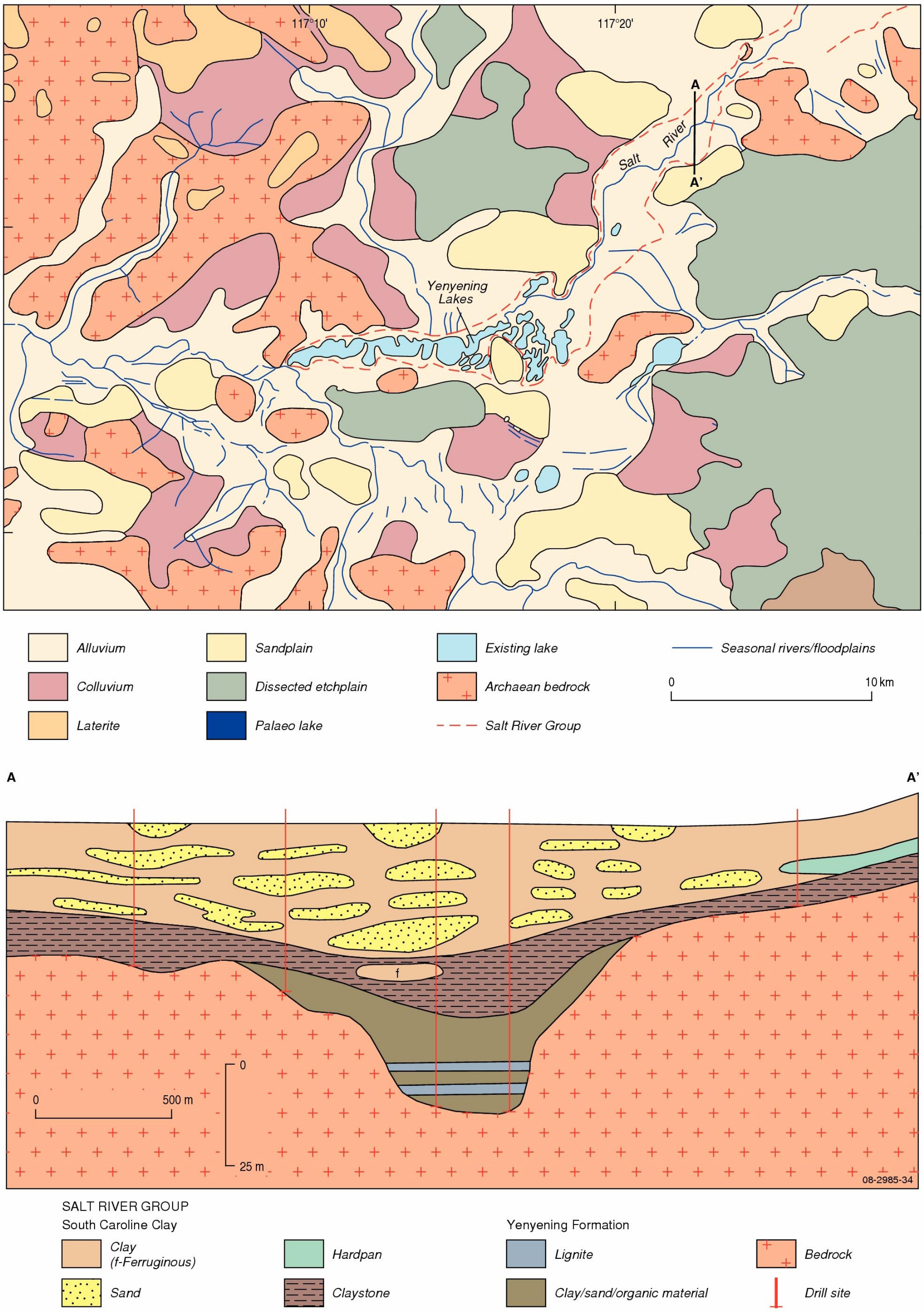


Figure 4.30: *Geomorphologic/regolith map (top view) of part of the Salt River system around Yenyenning Lakes. The outline of the distribution of buried Yilgarn River sediments is also shown. The lower view shows an interpreted cross-section across part of the palaeovalley (Line A-A') derived from a drilling transect. Note the distribution of various palaeovalley infill sequences shown here.*

The Yenyenning Formation is a lacustrine deposit and the well preserved pollen and plant macrofossils indicate Miocene or younger age. P. Commander (pers. comm. 2008) reported that subsequent palynological analyses have indicated a Pliocene age for the Yenyenning Formation with affinities to similar Pliocene deposits at Yarra Yarra, Toolibin and Lake Tay. The third unit, the South Caroline Clay, is also a lacustrine unit which variably outcrops along the length of the palaeovalley. It is thickest (up to 50 metres thick) in the palaeovalley centre and thins towards the margins. The South Caroline Clay is relatively uniform and consists of grey, whitish-grey and green clay and silt, with many isolated lenses of fine- to coarse-grained sand in the upper 10 metres. The unit is undated but overlies the Miocene Yenyenning Formation; Salama (1997) suggested a Pliocene age due to affinity with other Pliocene deposits.

Salama et al. (1992; 1993) and Salama (1994) also examined the evolution of the large playas or salt lakes in the Yilgarn Palaeovalley upstream of Caroline Gap. They reported widespread occurrence of similar Neogene palaeovalley sediments and suggested that deposition was followed by occlusion of the drainage and development of aridity and landscape salinity in the Quaternary. Palaeovalleys, as the lowest parts of the landscape, have focused groundwater flow and evaporative discharge, leading to sub-surface concentration of salts and the development of salt lakes. Salama et al. (1992) demonstrated that Lake Deborah East has a basement rock constriction of the palaeovalley at the downstream end which, in combination with impermeable lacustrine clay underlying the playa, has undoubtedly occluded groundwater outflow and greatly enhanced the long-term accumulation of salts due to evaporative discharge (Figure 4.31). The central part of Lake Deborah East contains a hard salt crust up to 70 centimetres thick, underlain by up to 1.65 metres of unconsolidated halite.

4.8.2.1. Salt River–Yilgarn River System Palaeovalley Groundwater

Salama (1994; 1997) and Salama et al. (1992) have studied the stratigraphic and geomorphic composition and evolution of palaeovalleys in the Salt River–Yilgarn River system. These investigations also focussed on the role of palaeovalley saline-rich groundwater in the formation of salt lakes. However, scant detail was provided on the aquifer or groundwater characteristics of the palaeodrainage network. Salama et al. (1993) gave some hydrogeological information for the Wallatin Creek sub-catchment of the Salt River–Yilgarn River system. They identified three aquifers in the groundwater system:

- A regional, weathered Archaean bedrock aquifer which is relatively deep, semi-confined to confined and lies adjacent to and below palaeovalleys;
- A palaeochannel sand aquifer, which is semi-confined below the palaeovalley clay layer; and
- An unconfined surficial aquifer in the sandplain overlying the clay layer of the palaeovalley sequence.

Groundwater salinity is lowest in the surficial aquifer at the top of the catchment (about 1,300 mg/L) but increases progressively downstream in the aquifer. Groundwater salinity in palaeochannel sand aquifers also increases progressively downstream with apparently higher TDS in uncleared (12,300–18,600 mg/L) versus cleared (7,800–16,500 mg/L) catchment regions. The salinity of palaeochannel sand aquifer groundwater is also higher (up to 50,000 mg/L) upstream of basement highs and bedrock dykes, due to flow-damming. A clear straight-line relationship between chloride and TDS levels for all groundwater suggests that increased salinity is due to evapotranspiration as groundwater flow downstream occurs.

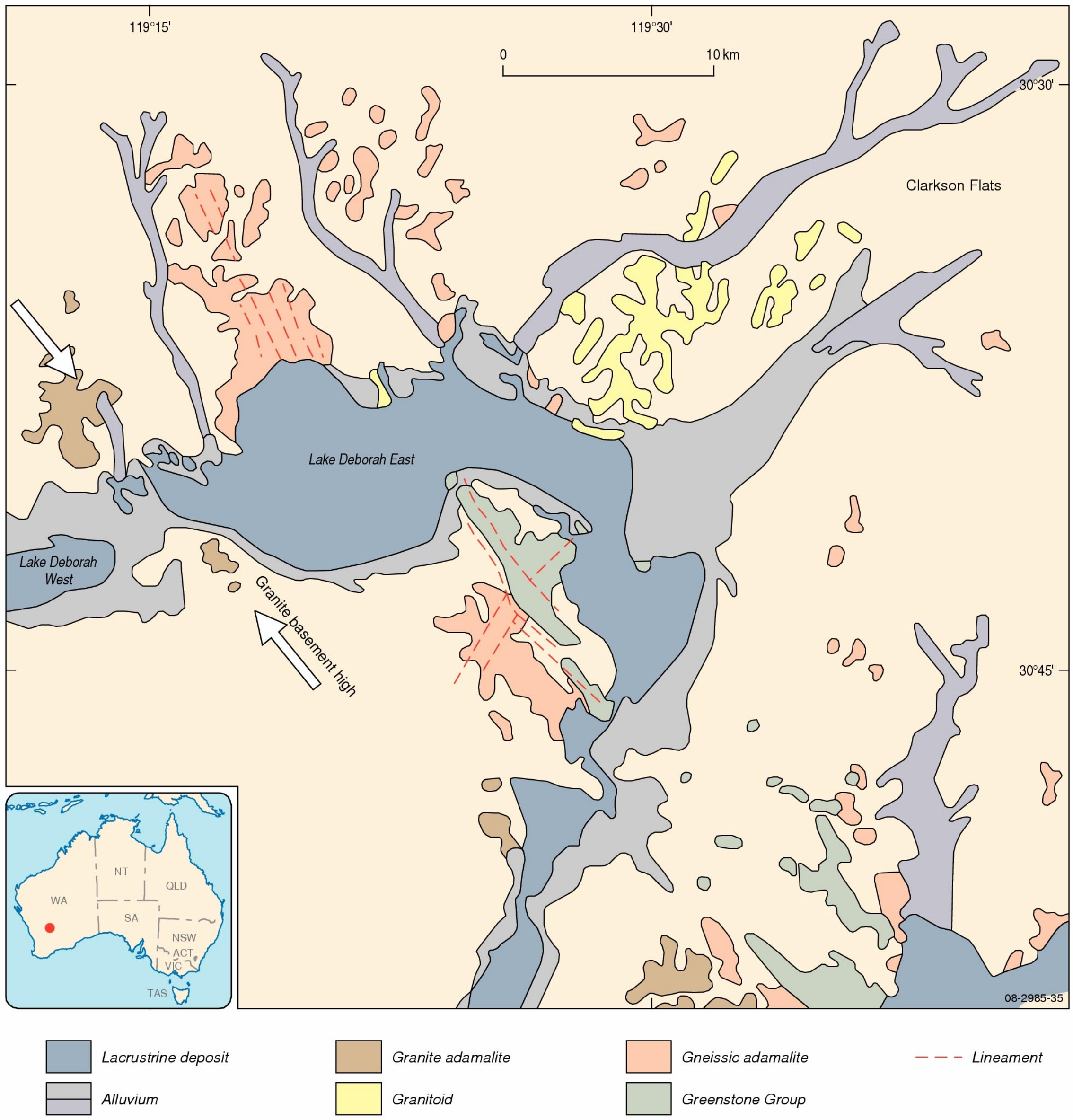


Figure 4.31: *Map of the distribution of lacustrine and alluvial sediments, and bedrock granite and gneiss outcrop, around the Lake Deborah East playa in the western Yilgarn. The arrows here show the location of a bedrock constriction point at the downstream end of the Lake Deborah East palaeovalley which restricts groundwater throughflow and has contributed to the development of significant salt stores within the lake. Figure is modified from Salama et al. (1997) (Figure 2 and Figure 5).*

4.8.3. Moore–Monger Palaeovalleys

The Moore–Monger Palaeodrainage (Beard, 2000) occurs north of the Yilgarn–Salt River system and forms a similar complex drainage pattern which has been variably modified by tectonic disruption, damming and diversion (Figure 4.32). Beard (2000) identified two tectonically formed river barriers associated with uplift of the Darling Range. East of the uplift many palaeodrainages, some marked by extremely large playas (e.g., Lake Moore), join at Lake Monger where the palaeovalley has been dammed by uplift and infilled with accumulated sediment, resulting in minimal gradients or no-flow conditions. Uplift-influenced damming of the Lake Monger Palaeovalley decreases northwards; the drainage has been deflected west and south-west to the Yarra

Yarra Lakes, which occur in the angled depression between the Darling Range and the Dandaragan Plateau (an uplifted and tilted block of the Perth Basin) (Yesertener et al., 2000). A poorly defined overflow channel south of Yarra Yarra Lakes follows the Darling Fault and links with the Moore River and a coastal outlet. Beard (2000) makes no reference to palaeovalley sediments and few published descriptions are available.

Figure 4.32: Map of the perennial and ephemeral modern drainage systems and the palaeodrainage networks identified in the Moore-Monger Catchment. The inset box here is shown as Figure 33. Figure is modified from Beard (2000) (Figure 1).

Commander and McGowran (1991) reviewed the hydrogeology of the Perenjori 1:250,000 mapsheet in the western Moore–Monger drainage division. However, they concentrated on the Perth Basin sequence in the south-east where significant quantities of low-salinity groundwater occur in multiple aquifers. Commander and McGowran (1991) recognised that calcrete and palaeochannel sand aquifers exist in the Yilgarn part of the Perenjori mapsheet but provided scant detail of their stratigraphic sequences or groundwater resources. Johnson and Commander (2006) examined groundwater resources in the larger Mid-West Minerals Province in the central-western portion of the state, including the coastal strip from Greenhead to Kalbarri (Perth and Carnarvon Basins) and the Murchison Province of the Yilgarn Craton. The northern Moore–Monger palaeodrainage system coincides with the southern Mid-West region. Johnson and Commander (2006) recognised that the stratigraphic architecture of the palaeodrainage network on the Murchison Province is largely unknown but is likely to be similar to that of the Northern Goldfields (Johnson et al., 1999). At Mount Gibson (Rockwater, 2005), the only regional site where the palaeovalley infill sediments have been investigated in detail, up to 100 metres of basal Eocene fluvial sand is confined by a lacustrine clay unit. These palaeovalley infilling sediments are overlain by up to 20 metres of slope-wash alluvium and valley calcrete. The palaeochannel sands are a major confined sedimentary aquifer with large supplies of saline to hypersaline groundwater, and are used for ore processing at the Mount Gibson mine. The palaeovalley calcrete deposits are major near-surface aquifers with large supplies of fresh to saline groundwater widely exploited for town supplies and mine processing in the Murchison Province, for example, at Mount Magnet, Cue and Meekatharra.

The Mount Gibson gold mine operated in 1986–1998, with the mining camp and operations (including a 1 million ton-per-year processing plant) supplied by seven production bores which tapped the palaeochannel sand aquifer of an unnamed palaeovalley (Figure 4.33). The palaeovalley sediment infill comprises 10–40 metres of basal fine- to coarse-grained sand which increases in thickness, width and grain size downstream. The basal sands are overlain by a dense confining unit of kaolinitic clay up to 40 metres thick (Groundwater Resource Consultants, 1988; Johnson and Commander, 2006). In 2005 a proposal to mine magnetite at nearby Extension Hill resulted in further exploration of the palaeochannel, with the aquifer found to extend at least 10 kilometres north of the existing borefield and probably another 20 kilometres further to Lake Monger (Rockwater, 2005). This part of the palaeovalley is about 60–80 metres deep and of variable width (average of 600 metres wide), with a low gradient of 0.004. The palaeovalley sediments are heterogenous and consist of sand, silt and clay layers; sandy aquifers are discontinuous but commonly hydraulically connected (Figure 4.34). Unlike most trunk palaeovalley infill sequences, the basal channel sediments are mostly clay-rich. Dark grey-brown aquifer sands with magnetite, gravel and secondary silcrete and calcrete occur mainly in the central and upper parts of the infill profile. The aquifer sands are generally confined by upper clays and silts which extend 5–10 metres below the watertable (Rockwater, 2005).

4.8.3.1. Moore–Monger System Palaeovalley Groundwater

Groundwater flow systems in the palaeovalleys are maintained by rainfall recharge, especially during high-magnitude events enhanced by surface runoff and local flooding. Discharge is dominated by playa evaporation and minimal throughflow occurs (Johnson and Commander, 2006). Groundwater in the palaeochannel aquifer is predominantly saline, 4,000–36,000 mg/L in bores, and thought to exceed 200,000 mg/L near Lake Monger at the downstream end of the palaeovalley. However, around the Extension Hill mine groundwater salinity varies irregularly rather than increasing progressively downstream, as occurs in many palaeochannel aquifers. Generally, the surficial and weathered bedrock aquifers flanking the palaeovalley contain lower salinity groundwater and have lower permeability, e.g., <1 m-per-day for surficial aquifers and <0.1 m-per-day for weathered bedrock aquifers.

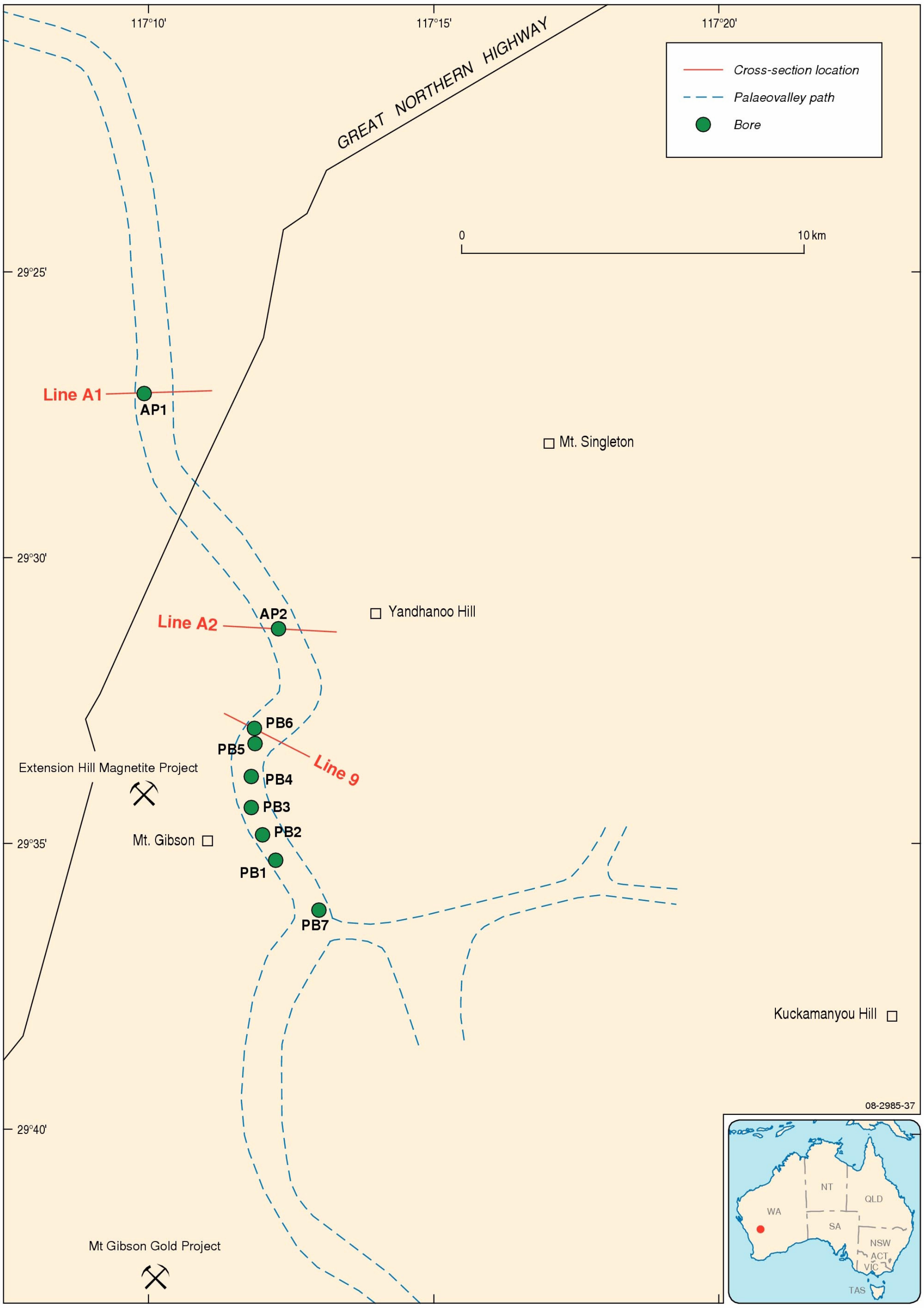


Figure 4.33: *Map showing the unnamed palaeovalley near the former Mount Gibson mine in Western Australia which was used to supply groundwater for ore processing via seven production bores. The location of three cross-section lines which show the distribution of Cenozoic sediment infill within this palaeovalley (refer to Figure 4.34) are also shown. Figure is modified from Rockwater (2005) (Figure 1).*

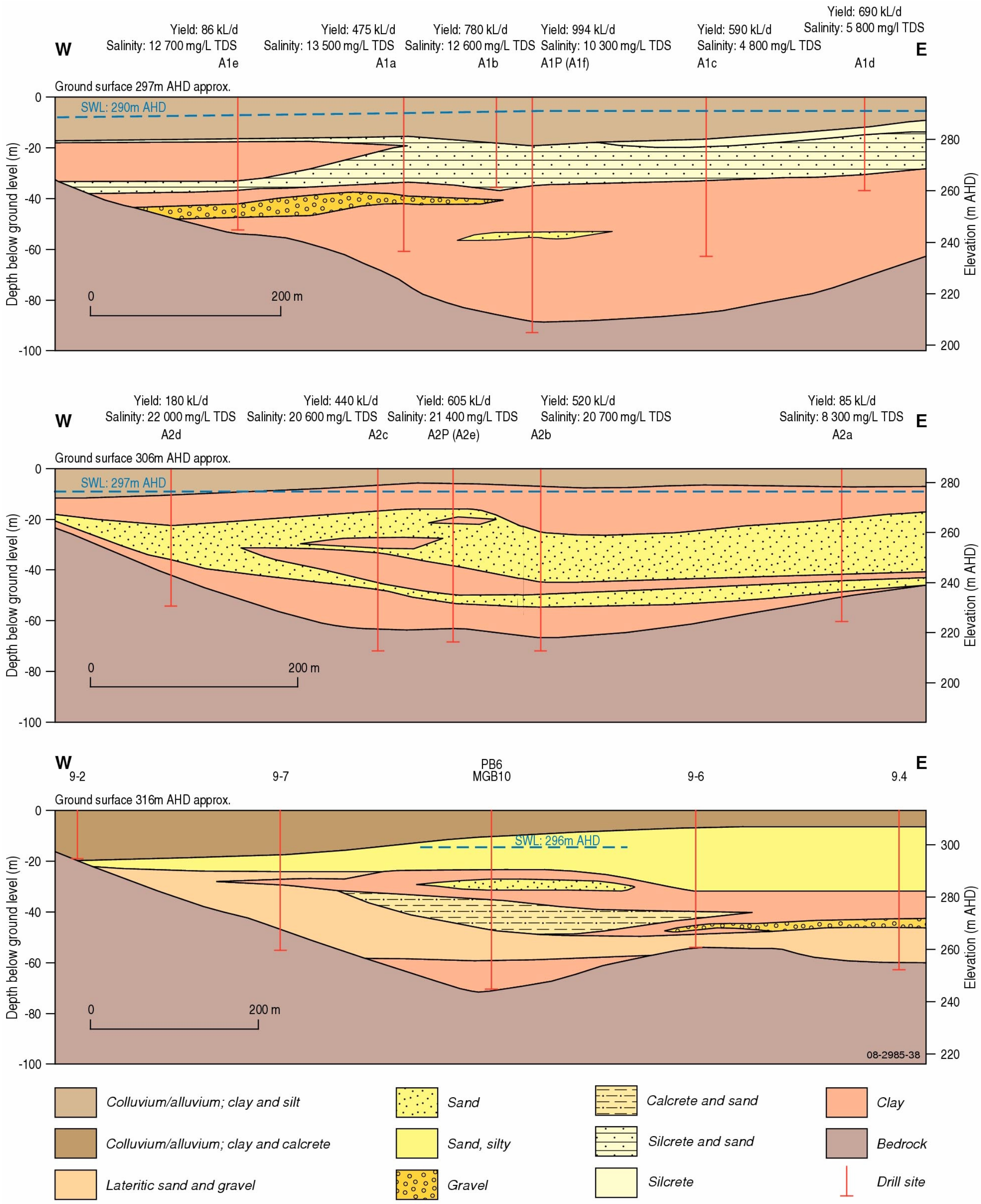


Figure 4.34: *Three cross-section profiles through the unnamed palaeovalley which was used to supply water for mining operations at the Mount Gibson gold mine in Western Australia Extension. These three views highlight the variability of the sediment profile which occurs in this palaeovalley. The location of various production and investigation boreholes is also shown, along with details of groundwater yield and salinity. Figure is modified from Rockwater (2005) (Figures 4, 5, and 6).*

Detailed hydrogeological information from the Moore–Monger system in the Western Yilgarn is limited, apart from a consultant report on the extraction of palaeovalley groundwater for magnetite mining at Extension Hill, south-west of Payne's Find on the Great Northern Highway (Rockwater, 2005). The palaeovalley extends at least 30 kilometres northwards at a gradient of ~0.004 and is a tributary to the Lake Monger system (Figure 4.32). Channel width is variable (average 600 metres-wide) and the base occurs 60–80 metres below ground. The channel cuts into the Archaean basement which consists of granite, mafic and metasedimentary rocks, including some banded iron formations. Palaeovalley alluvium is undated and includes clayey silt and sand units, and some parts of the palaeochannel sand sequence may form local aquifers.

Unlike most palaeovalley infill, the basal unit is clay-rich and contains minimal sand and gravel. Palaeochannel aquifers occur mainly in the central and upper portions of the palaeovalley alluvial sequence and consist of dark greyish-brown sand with magnetite and gravel. Silcrete and calcrete may replace parts of the clay-rich zone and also form local aquifers. The palaeochannel aquifers are discontinuous but hydraulically interconnected. An upper 5–20 metres of silt- and clay extends below the watertable and confines the main aquifer units. The standing groundwater level in the palaeovalley is commonly 10–15 metres below surface and slopes northwards at a gradient of ~0.009. The basal clay unit probably limits the amount of lateral and vertical connection between the palaeochannel aquifer and the underlying or adjacent weathered bedrock aquifer.

Air lift yields from bores in the palaeochannel aquifer range up to 780 m^3-per-day (Table 4.8). The calculated values of aquifer permeability vary widely (0.5–36 m-per-day); this reflects the heterogeneity of the aquifer sediments, as zones of gravel, silcrete and calcrete have relatively high permeability and zones of silt- and clay-rich sand have much low permeability. The derived permeability values shown in Table 4.8 represent an average for several lithological types over the screened bore interval.

Table 4.8: Extension Hill palaeochannel aquifer transmissivity and permeability values derived from pumping tests (after Rockwater, 2005).

BORE NUMBER	AQUIFER TRANSMISSIVITY (m^2/day)	AQUIFER PERMEABILITY (m/day)
A1P	420	12
A2P	58	1.6
PB1	95	3.5
PB2	80	5
PB3	500	36
PB4	45	1.2
PB5	35	0.9
PB6	25	0.5
PB7	20	0.7

Palaeovalley groundwater abstraction at the nearby Mount Gibson gold mine was relatively modest during the operational life of the project (early 1987 to mid 1998). Subsequent investigation of groundwater resources seven years after operations finished provided an opportunity to assess the longer-term impact of groundwater abstraction and subsequent recovery of groundwater resources of a palaeovalley aquifer. Using various pumping combinations the seven production bores, PB1 to PB7 (Figure 4.33), produced 400–800 x 10^3 m^3-per-year during the life of the gold mine and about 7,000 m^3-per-year from mine shutdown until resurvey in 2005. By mid 1998, abstraction had lowered groundwater levels in observation bores within the PB1-PB7 borefield by about 17 metres. Recovery of groundwater levels to about 8 metres below the pre-mining levels had occurred by 2005 (Rockwater, 2005). Local pastoral bores located outside the palaeovalley are believed to derive water from weathered bedrock aquifers with negligible lateral connection to the palaeovalley due to the strike direction of the bedrock and the presence of the upper confining unit (Rockwater, 2005;

Johnson and Commander, 2006). The groundwater level in eight pastoral bores adjacent to the palaeovalley, monitored between 1987 and 2004, showed no discernible drawdown associated with groundwater abstraction for the Mount Gibson gold mine (Rockwater, 2005). Palaeochannel aquifer groundwater salinity is too high for stock-watering purposes.

Similar to Mt Gibson, the Windimurra vanadium mine uses palaeovalley groundwater for mining operations, but little detailed hydrogeological information is available publicly. The Windimurra Palaeovalley is located about 4 kilometres east of the mine where it trends north-westerly before arcing around to join the Moore Palaeovalley system. The Rockwater consultancy firm was commissioned to find up to 7,000 m^3-per-day for operations and mineral processing at Windimurra. Acquisition of geophysical data (involving ground-based electromagnetic surveys such as TEM and SIROTEM MKIII) was used to locate the buried palaeochannel. The TEM data defined the depth to bedrock by providing an approximate cross-section of the palaeovalley and also identified the palaeochannel aquifer which contains saline water (prominent conductor). These geophysical survey results were used to plan the groundwater drilling program. Unfortunately, no details of the stratigraphic architecture or groundwater resources are available.

The Windimurra Palaeovalley is about 500 metres wide and contains up to 130 metres of sediments, with three aquifers used to supply mine operations. The basal palaeochannel aquifer is 20–40 metres thick and contains saline groundwater (up to 70,000 mg/L) used for ore processing. The basal sands are overlain by 60–80 metres of clay. The upper aquifer consists of 10–15 metres of alluvium, calcrete and ferricrete. Bores in the upper alluvial and calcrete aquifers provide lower yields of fresher groundwater, which is used for potable supplies at the mine camp. The Windimurra Palaeovalley aquifers have stygofaunal communities and the impact of groundwater abstraction on those ecosystems was assessed in the approval process.

4.9. EASTERN YILGARN TO WESTERN EUCLA BASIN MARGIN

The geological composition of Eastern Yilgarn basement is similar to the western Yilgarn, consisting mainly of granitic and greenstone rocks. The palaeodrainage network east of the central Yilgarn watershed feeds the Eucla Basin, a southern Australian marine Cenozoic basin with uplifted Miocene sediments exposed on the Nullarbor Plain and relatively thick offshore sequences (Figure 4.35). The palaeodrainage network is not traceable across the Nullarbor Miocene limestone, demonstrating that the formation of the palaeovalleys and the deposition of their infilling sediments occurred prior to the Miocene. The original pre-Cenozoic palaeovalleys (i.e., the ‘primary valleys’ of de Broekert and Sandiford, 2005) probably drained to the lower Eucla and Bight Basins; these formed part of the emerging seaway between Australia and Antarctica in the Mesozoic and thick marginal marine sediment sequences were deposited (de Broekert and Sandiford, 2005).

Six major palaeovalley systems drain the eastern Yilgarn Craton towards the Eucla Basin (Figure 4.35). From south to north these are the Cowan, Lefroy, Roe, Rebecca, Raeside, and Carey palaeovalleys and their associated tributary networks. The palaeovalleys form a radial pattern focused on the Eucla Basin and trend north-easterly in the south and south-easterly in the north. All the palaeovalleys are characterised by multiple large playas along the valleys. The Cowan Palaeovalley, formerly tributary to the Lefroy system, was reversed by tectonic activity associated with rifting. The Lefroy and Cowan palaeovalleys contain marine sediments derived from multiple Eocene eustatic transgressions, in addition to fluvio-lacustrine sediments. Marine sediments are absent from palaeovalleys further north. The sedimentary sequences in the Cowan, Lefroy and Roe palaeovalleys (Figure 4.36) have been extensively studied in exploration drillholes, open-cut mine pits and hydrogeological investigations associated with mine water supplies or environmental impact assessments.

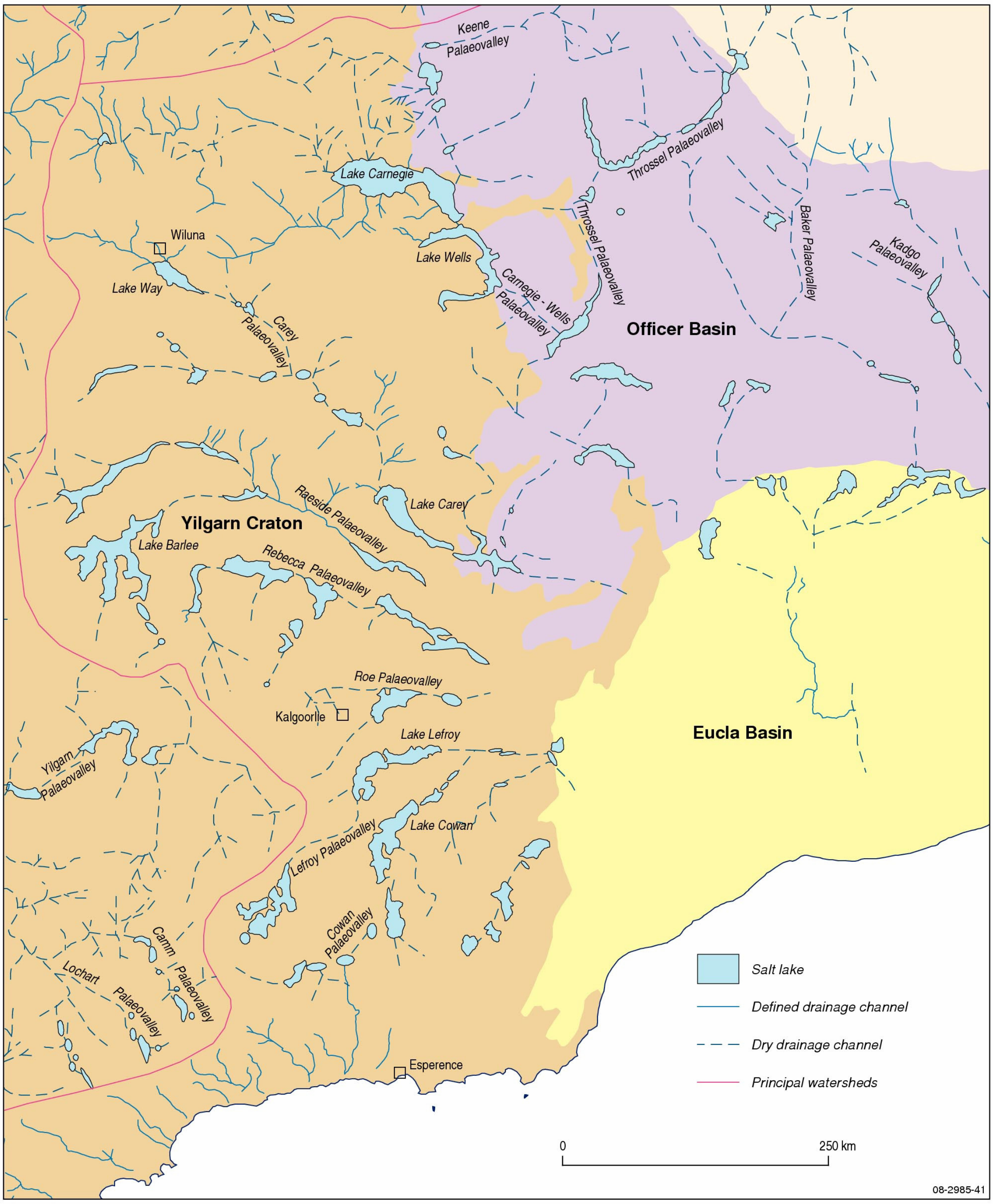


Figure 4.35: *Regional map of the eastern Yilgarn Craton with adjacent parts of the Officer Basin and the Eucla Basin. The major palaeovalley systems and associated salt lakes of the western Yilgarn are shown. The palaeodrainage network was tributary to the western Eucla Basin, although its distribution cannot be traced across the present-day Eucla Basin because of extensive Miocene limestone deposits which cover the older palaeovalleys. Figure is modified from Beard (1973).*

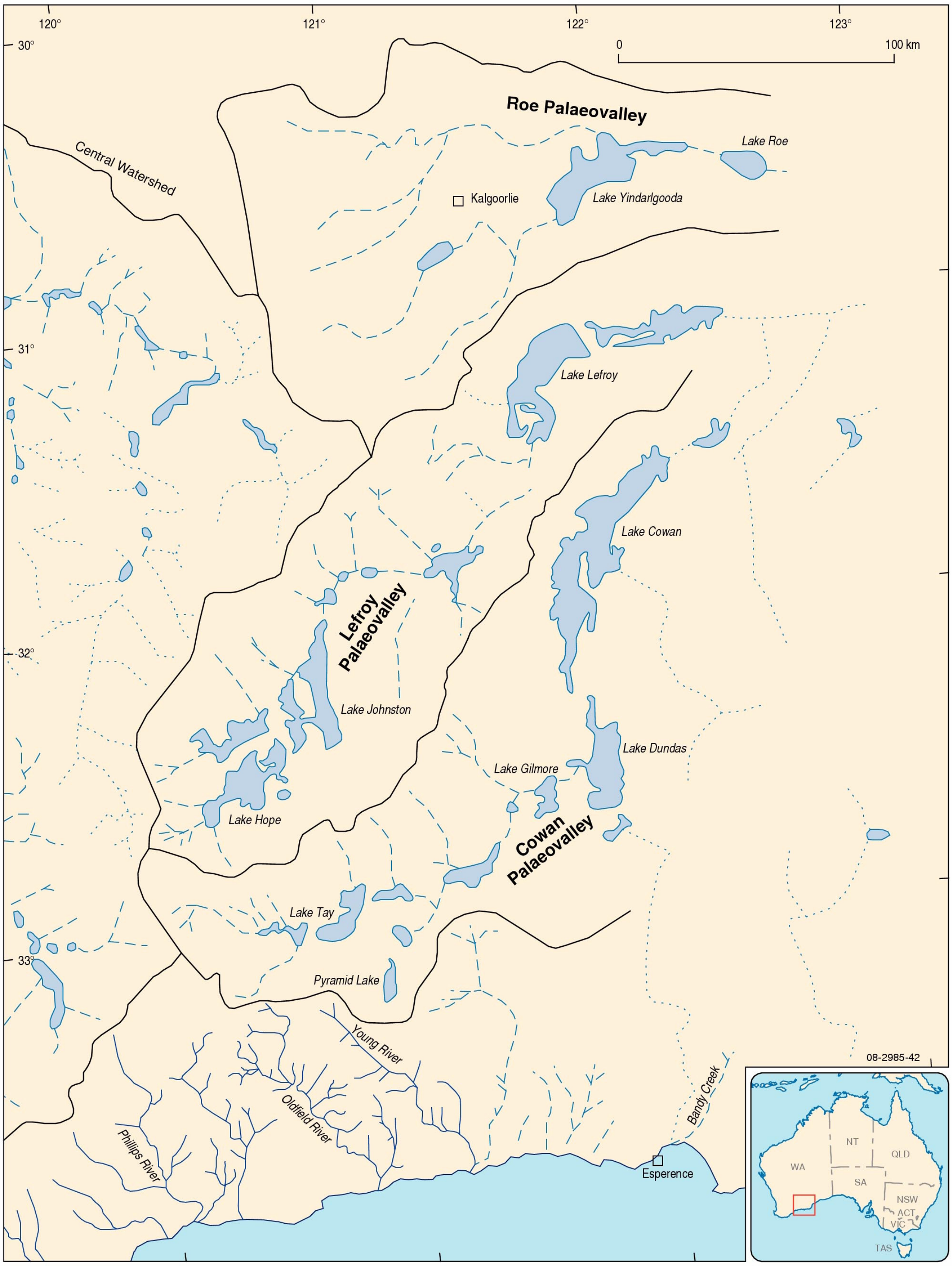


Figure 4.36: *Map of the western Yilgarn Craton showing the spatial distribution of the palaeodrainage networks and present-day salt lakes of the Cowan, Lefroy and Roe palaeovalleys. Figure is modified from Beard (1999) (Figure 1).*

Palaeovalley groundwater resources of the Eastern Yilgarn have been more extensively studied, exploited and monitored than for any other Australian region. This is particularly true for the Roe Palaeovalley in the Kalgoorlie area where many mining operations have been supported by palaeovalley borefields. Groundwater abstraction from the Roe Palaeovalley began in 1984 and expanded in the late 1980's due to the combination of new gold processing technologies (carbon in pulp – CIP; carbon in leach - CIL) and expansion in the number of mines. Groundwater abstraction peaked through the mid-1990's and then declined due to improvements in CIP/CIL and the development of alternative water sources, e.g., surface water from playa flood events, mine void water and open pit de-watering. Concerns for the sustainability of Roe Palaeovalley groundwater resources led to detailed monitoring of borefield parameters and the water-level response to abstraction (Johnson, 2007). This monitoring program, combined with earlier hydrogeological studies of the Roe Palaeovalley (e.g., Commander et al., 1992; Turner et al., 1994; Turner et al., 1996) has resulted in detailed understanding of the Roe Palaeovalley groundwater system. This provides an extremely valuable insight of palaeovalley groundwater systems but must be extended to other regional palaeovalleys with caution. Even within the Eastern Yilgarn there are stratigraphic differences between different palaeovalleys which have the potential to influence the nature of groundwater systems. For instance, southward of the Roe Palaeovalley there is a progressively more significant marine influence in the nature of Eocene infill sediments, whereas northward there are more extensive palaeovalley calcrete aquifers.

4.9.1. The Cowan and Lefroy Palaeovalleys

The Cowan and Lefroy palaeovalleys were studied by Clarke (1993, 1994) and included as part of a major revision of the Eucla Basin Eocene stratigraphy (Clarke et al., 2003). Initial incision of the Lefroy and Cowan palaeovalleys occurred pre-Jurassic (Clarke 1994); the >10 kilometre-wide southern end of the Cowan Palaeovalley, which is truncated by the modern coastline at Esperance, implies considerable pre-rifting extension into Antarctica (Ollier, 1988). Clarke (1994) also considered that the reversal of the Cowan Palaeovalley was due to initial rifting in the Jurassic and formation of the Bremer Basin, with associated uplift of the Yilgarn Craton along the Jarrahwood Axis, although Cope (1975) believed that uplift occurred in the Eocene. No pre-Cenozoic sediments are preserved in these palaeovalleys.

In the Cowan Palaeovalley (Clarke, 1993, 1994) sedimentation began in the Early to Middle Eocene. Carbonaceous clay, silt and sand deposits (with lignite) of the Werrillup Formation were unconformably deposited on the underlying weathered basement rocks (Figure 4.37). This was followed by deposition of marine sediments during the Tortachilla transgression, which flooded much of the Cowan Palaeovalley and reduced clastic input, resulting in deposition of the fossiliferous, lithologically variable, and partially dolomitised Norseman Limestone in the Mid to Late Eocene. Regression allowed renewed sedimentation of deltaic and estuarine lignite-bearing mangrove facies, forming the thickest sequences of Werrillup Formation. The Aldinga transgression in the Late Eocene was more extensive that the Tortachilla transgression and caused widespread deposition of the Princess Royal Spongolite. This unit contains >50% siliceous sponge spicules with silt, clay, sand and glauconitic peloids. Post-Eocene sedimentation is considerably different and marked by oxidised non-marine, fine-grained clastic deposits of the Revenge Formation, and white to buff-coloured dolomite and dolomitic carbonate mudstone of the Cowan Dolomite. These sediments were correlated to the Miocene by Clarke (1993, 1994) by comparison to widespread dolomitic lacustrine facies of that age in the eastern Eucla Basin and the Lake Eyre Basin. Gypsum-bearing evaporite deposits of the Polar Bear Formation, including aeolian lunettes and dune islands, were considered by Clarke (1993, 1994) to be Pliocene or younger.

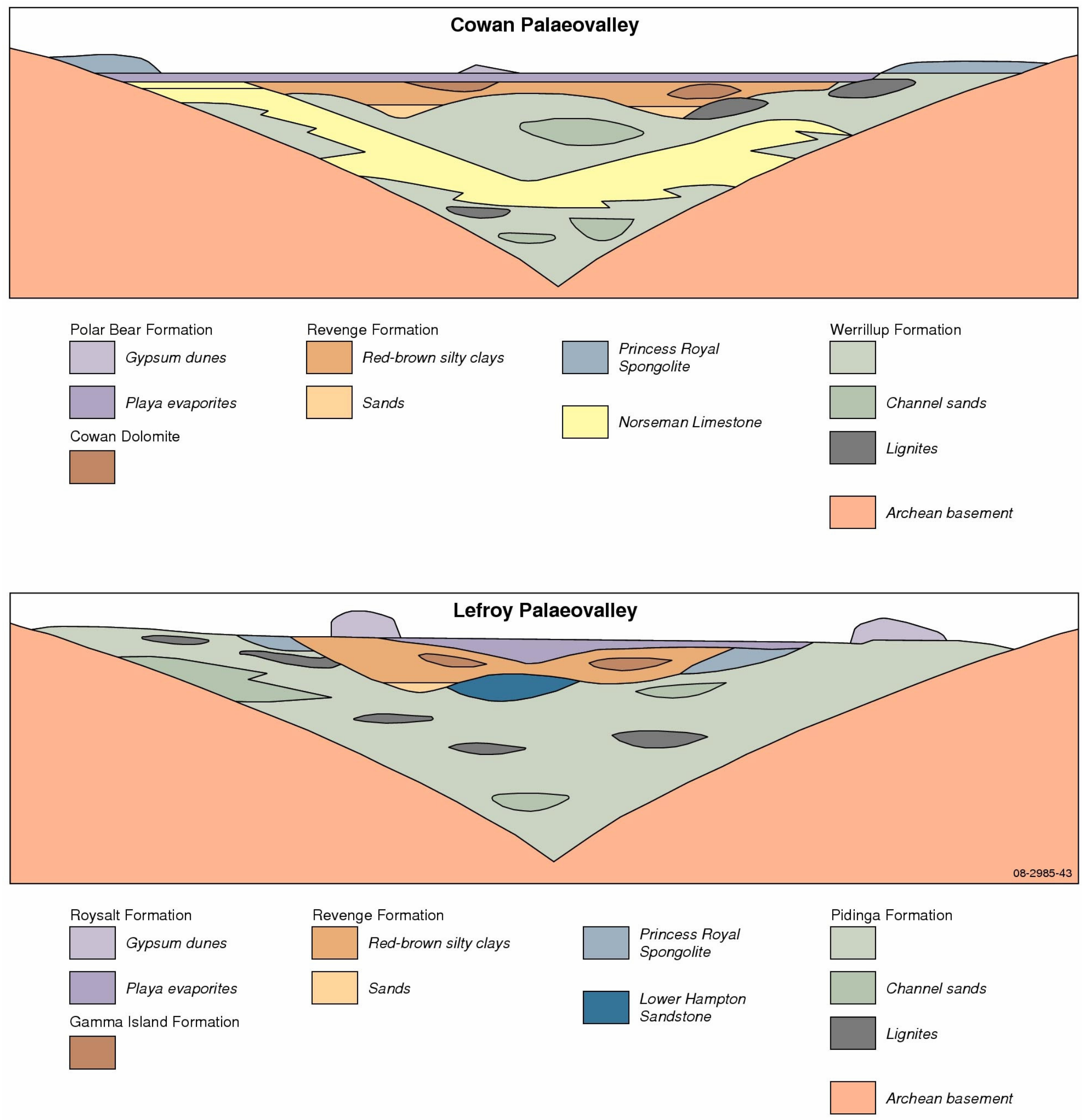


Figure 4.37: *Idealised stratigraphic sections of the Cowan and Lefroy palaeovalleys demonstrating the stratigraphic relationship of the palaeovalley sediments and the main sedimentary formations. Figure is modified from Clarke (1994) (Figure 8 and Figure 9).*

The stratigraphic sequence in the Lefroy Palaeovalley is similar to that found in the Cowan palaeovalley (Clarke, 1993; 1994). The oldest sediments are of fluvial origin and form the Lower to Middle Eocene Pidinga Formation. This unit consists of red-brown to green silt, white grey or black silty clay and lignite. Minor gravel-rich sand bodies and pyrite also occurs. The Pidinga Formation unconformably overlies weathered Archaean basement rocks and interfingers with the Middle to Upper Eocene Hampton Sandstone, which contains marine fossils and is correlated to the Tortachilla and Aldinga eustatic marine transgressions. Clastic sedimentation dominated during the Tortachilla transgression in the Lefroy Palaeovalley as the marine incursion was spatially restricted. In the more extensive Aldinga transgression, clastic input was relatively restricted and the Princes Royal Spongolite was deposited in some parts of the Lefroy Palaeovalley. As occurred in the Cowan Palaeovalley, the post-Eocene depositional environment was fluvio-lacustrine; fine-grained clastic sediments of the Revenge Formation and dolomite and dolomitic carbonate mudstone of the Gamma Island Formation were deposited. These sediments were undated by Clarke (1993; 1994) but were correlated to the Oligo–Miocene. The sequence is capped by gypsum-bearing evaporite sediments of the Roysalt Formation and gypsum-bearing lunette dunes of the Beta Island member, with Clarke (1993, 1994) suggesting a basal Pliocene or even Miocene age. As with the Polar Bear Formation in the Cowan Palaeovalley, it seems more likely that these sediments relate to playa development and were formed in the Quaternary.

Eucla Basin marginal palaeovalleys have a complex succession of non-marine and marine sedimentary units due to their:

- Large areal distribution, extending from the eastern Gawler Craton to the eastern Yilgarn Craton;
- Development during multiple eustatic sea level transgressions which affected different topographic levels; and
- Modification caused by epeirogenic post-rifting tectonic deformation.

This complexity has resulted in confused correlation of units and events both within and between regions. Figure 4.38 demonstrates this problem by comparing the Cowan and Lefroy palaeovalley stratigraphic sequences of Clarke (1993, 1994) with a later revision of the Eocene portion (Clarke et al., 2003) and the most recent summary of the stratigraphy by Hou et al. (2006) and Hou et al. (2008).

4.9.2. The Roe Palaeovalley

Palaeodrainage patterns are long recognised in the Western Australian landscape (Section 2.1). However, the correlation of deeply incised palaeovalleys with significant sediment infill is more recent. Early mining operations in the WA Goldfields recognised that mineable gold occurs in relatively deep alluvial sediment sequences and these were termed ‘deep leads’, presumably by analogy to the deep leads of the Victorian goldfields which were also buried palaeochannel deposits (although situated in Australia’s Eastern Highlands). Blatchford (1900) described deep leads at Kanowna and drew cross-sections which demonstrated channel-like patterns and fluvial sedimentary characteristics. Rollo’s Bore near Coolgardie was described by Blatchford (1899) and Maitland (1901) as containing carbonaceous valley-fill deposits equivalent to deep lead sediments to about 100 metres depth. Balme and Churchill (1959) determined a Late Eocene to Early Oligocene age from pollen from the Rollo’s Bore sequence and samples from the Perkolilli Shale were reanalysed by de Broekert (2001). The relatively deep sequence at Rollo’s Bore lead to early conjecture of a structural depression (see discussion in de Broekert, 2001) but de Broekert (2001) described the fill as typical of palaeovalley over mafic basement in the Roe Palaeodrainage. Kern and Commander (1993) also suggested that the Rollo’s Bore sequence was palaeovalley infill, and the anomalous depth was due to misidentification of the basal weathered Archaean bedrock and mislabelling of the basal carbonaceous material. Playford et al. (1975) proposed the name Rollo’s Bore Beds for the ancient valley fills or deep lead sediments at Coolgardie and other parts of the eastern Goldfields. The name was changed to Rollo’s Bore Formation by Cockbain and Hocking (1989). Details of the continuity and nature of trunk and tributary palaeovalley fills and their concordance with the palaeodrainage networks did not come until groundwater investigations commenced in the Roe Palaeovalley in the late 1980’s (Commander et al., 1991; Kern and Commander, 1993).

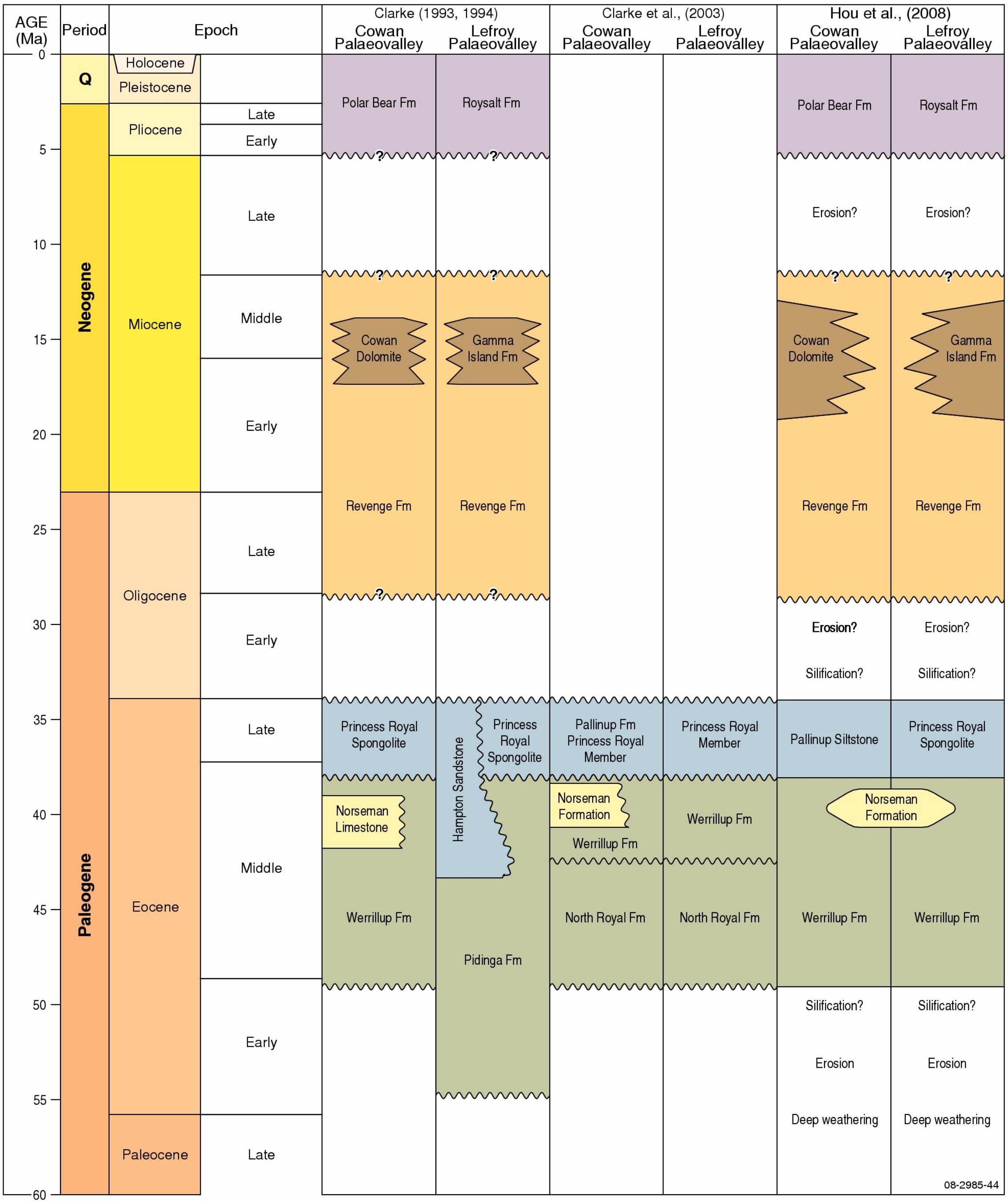


Figure 4.38: *Comparison of the different stratigraphic correlations and nomenclature previously used for the palaeovalley infill sediments of the Cowan and Lefroy palaeovalleys. Data sourced from Clarke (1993; 1994), Clarke et al. (2003), and Hou et al. (2008).*

The Roe Palaeovalley in the Kalgoorlie region was investigated with multiple drillhole transects across many of the upper and middle tributaries by Commander et al. (1992) (Figure 4.39). The lack of marine sediments indicated that the area was above the level of the Eocene transgressions which inundated the Cowan and Lefroy palaeovalleys further south. Clarke (1994) suggested local elevations of approximately 280 metres and 300 metres AHD for the Tortachilla and Aldinga transgressions respectively, suggesting Post-Eocene local uplift of up to 150 m. The minimum elevation in the Roe Palaeovalley investigation of Commander et al. (1992) is 310 metres AHD, just above the upper occurrence of Princess Royal Spongolite deposited at the height of the Aldinga transgression (further south). It is probable that marine facies occur in the Roe Palaeovalley downstream of Lake Roe.

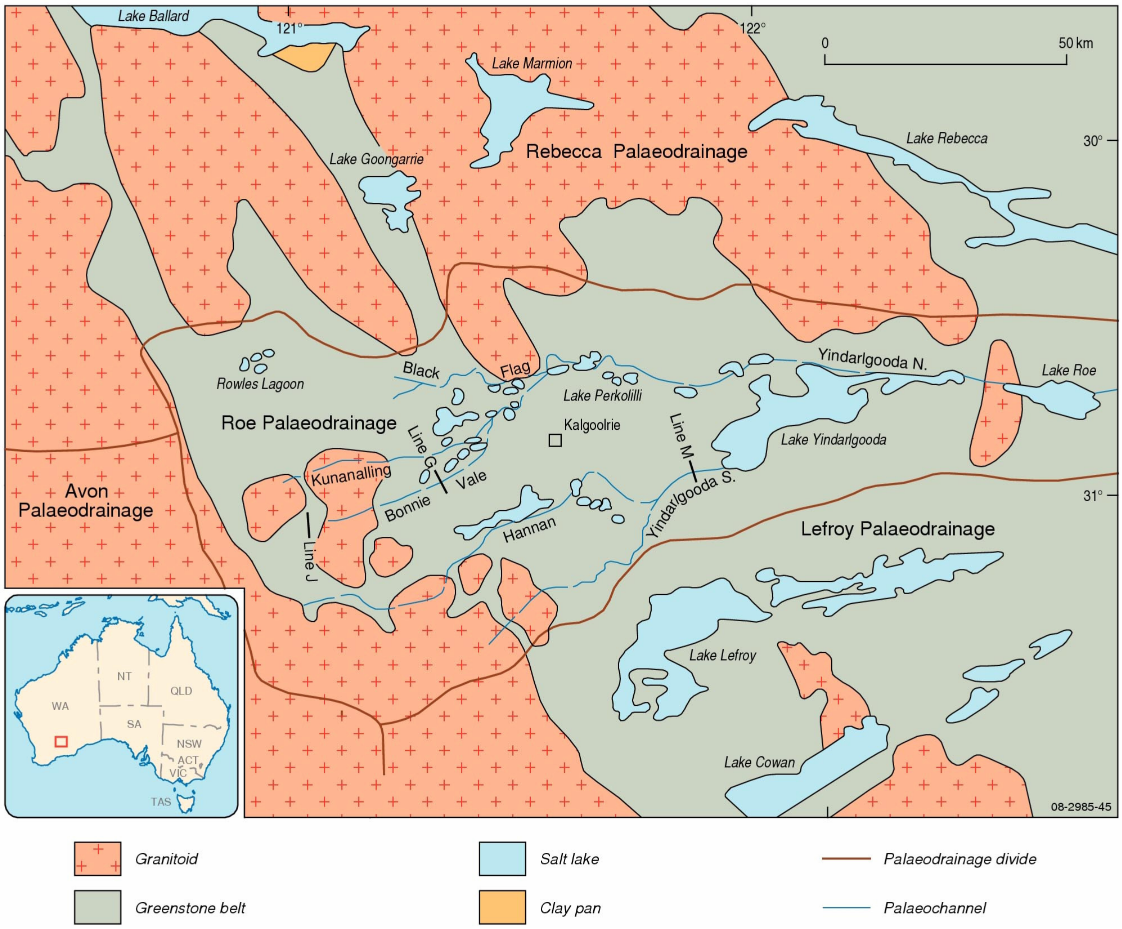


Figure 4.39: *Map of the Roe Palaeodrainage system in the eastern Yilgarn, superimposed on the basement granitoid and greenstone geology. The various tributaries and salt lakes of the Roe Palaeovalley are identified here. The three drilling transects across several of the tributary streams (Lines J, G and M) refer to interpreted cross-sections shown in Figure 4.40. Figure is modified from Commander et al. (1992) (Figure 3).*

The upper parts of the Roe Palaeovalley are mostly V-shaped (Figure 4.40) and vary from 400–700 metres wide and 25–40 metres deep, increasing downstream to 1,000–1,500 metres wide and 55–75 metres deep, east of Kalgoorlie (Kern and Commander, 1993). The Cenozoic infill sediments of the Roe Palaeovalley are up to 70 metres thick and consist of basal fluvial sand overlain by lacustrine clay, with Quaternary sediment cover capping the valley infill. De Broekert (2002) undertook a detailed analysis and subdivision of the facies variations and depositional environments in both units.

The basal unit of the Roe Palaeovalley is the **Wollubar Sandstone** (Commander et al., 1992). It rests unconformably on deeply weathered Archaean basement, with a maximum thickness of 38 metres. The Wollubar Sandstone is grey, buff, yellow and brown and contains abundant fine- to very coarse-grained quartz sand. The unit is not lithified, although it contains minor cross-bedding.

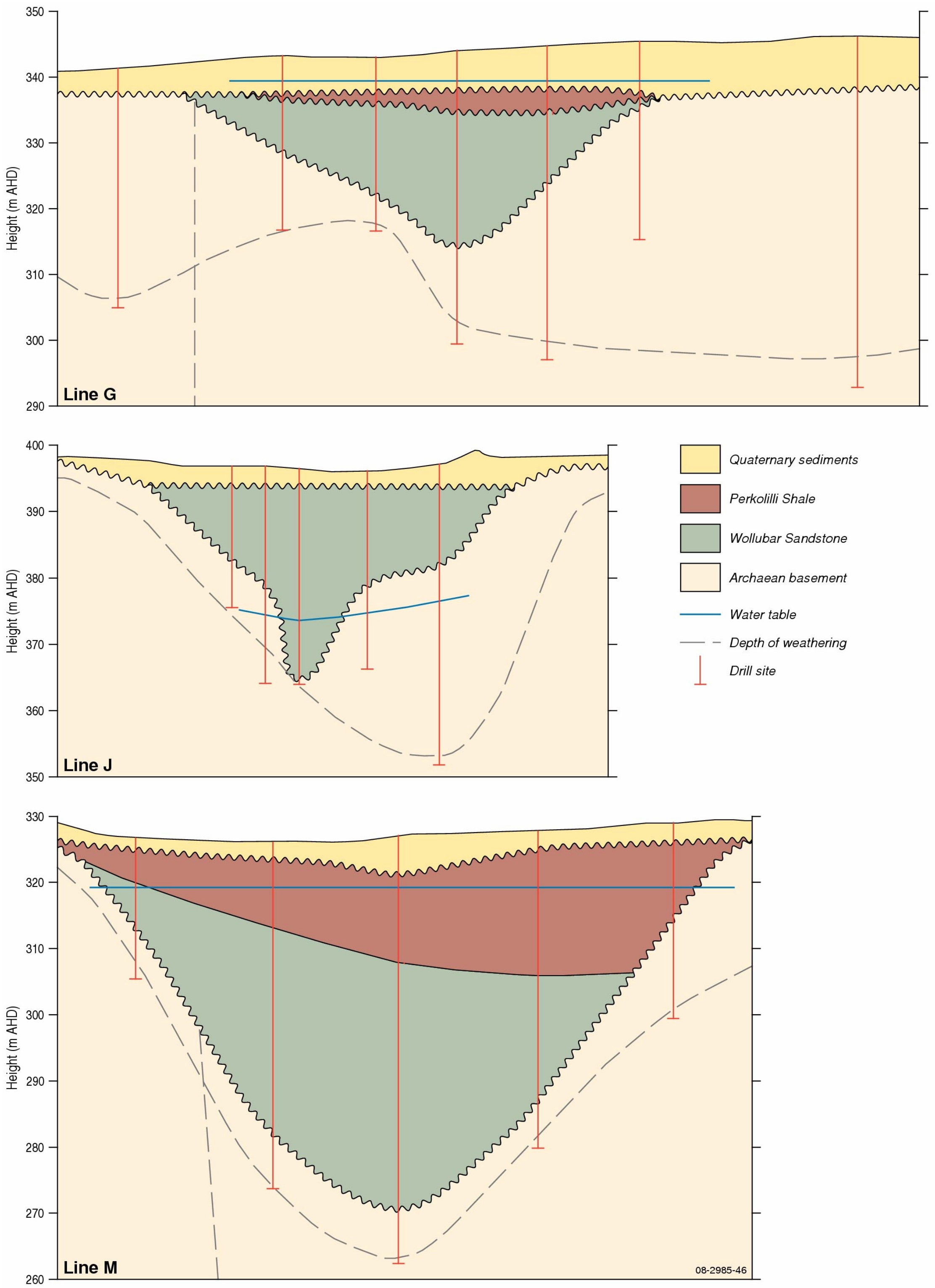


Figure 4.40: *Schematic cross-sections of the Roe Palaeovalley sediment infill sequence, based on the interpretation of drilling transects. Note the abundance of the basal Wollubar Sandstone unit and the variable thickness of the upper Perkolilli Shale. The location of the cross-section lines is shown in Figure 4.39. Figure is modified from Commander et al. (1992) (Figure 9).*

The quartz-dominated sediments of the Wollubar Sandstone are subangular to subrounded, and moderately to poorly sorted. Gravel-rich zones are common, especially near the base, and sandy clays occur in the upper part of the sequence, especially at palaeochannel flanks. Thin beds of carbonaceous clay and lignite occur sporadically in the sandstone, especially in the eastern part of the palaeovalley, and near the flanks. The Wollubar Sandstone was deposited in a mostly fluvial environment with minor influence from paludal and lacustrine systems (Kern and Commander, 1993). The unit was palynologically dated to the late Medial to early Late Eocene and correlated to the Hampton Sandstone in the Lefroy Palaeovalley by Commander et al. (1992). De Broekert (2002) reanalysed the pollen assemblages and, cognisant of the relatively poor chronological constraints for south-west Western Australia, agreed with the Mid to Late Eocene age for the Wollubar Sandstone.

The upper unit of the Roe Palaeovalley, the **Perkolilli Shale**, consists of mottled, grey, dark-brown and yellow clay with minor sandy clay interbeds (especially in the upper part). It has a maximum thickness of 39 metres. The upper Perkolilli Shale is weathered and the boundary with overlying Quaternary deposits (typically at depths of 4–6 metres) is difficult to distinguish. Silicification occurs in the lower part just above the contact with the Wollubar Sandstone, with cryptocrystalline quartz and opal replacing primary clay. Well rounded, concentrically layered, ferruginous pisolites, assumed to have formed *in situ*, are widely distributed. The upper portion is variably ferruginised, ranging from slight ferruginous mottling to massive limonite induration. Ferruginisation is commonly developed above the watertable. In one location massive dolomitic calcrete, varying from friable and powdery to indurated and vuggy, replaces the clay and was considered a groundwater calcrete deposit by Commander et al. (1992). The unit formed in a lacustrine environment, interpreted as being due to drowning of the river system by relatively distant sea-level rise (Kern and Commander, 1993). However, they also noted that the nearest Eocene marine deposits in the Roe Palaeovalley occur near Counselee, some 180 kilometres east of Kalgoorlie. Hence, although valley incision can propagate the effects of lowered sea-level further upstream, there is no obvious mechanism for sea-level rise to impact a river valley significantly above the zone of estuarine inundation.

De Broekert (2002) undertook detailed study of the Roe Palaeovalley and determined that the initiation of inset-valley incision was due to late medial Eocene epeirogenic uplift of the Yilgarn. This was tentatively linked to a change in the horizontal stress field resulting from a major plate tectonic re-organisation. De Broekert (2002) suggested that the architecture and facies of both the fluvial Wollubar Sandstone and lacustrine Perkolilli Shale were incompatible with tectonic allogenic control as a cause of deposition. De Broekert (2002) also rejected the effects of eustatic, relative sea-level rise as an allogenic control of inset-valley deposition because:

- The Roe Palaeovalley is too remote in altitude and distance from the raised coastal zone;
- There is no supporting stratigraphic or sedimentologic evidence in the Wollubar Sandstone; and
- Sea-level rises were not coeval with deposition of the Perkolilli Shale.

De Broekert (2002) demonstrated that climate change has the capacity to control deposition by altering the balance between discharge and sediment supply, and that this effect can occur throughout the valley. He concluded that the onset of more seasonal rainfall patterns led to deposition of the Wollubar Sandstone; the various sedimentary facies, sediment materials, and pollen assemblages are consistent with seasonal climate regimes. The Early Oligocene was cold and dry due to initiation of the circum-Antarctic current and glaciation in Antarctica. De Broekert (2002) suggested that the resulting low levels of precipitation and low evaporation rates resulted in the development of sluggish wetland or lacustrine conditions, and formation of the Perkolilli Shale.

The boundary of the Perkolilli Shale and the Wollubar Sandstone is mostly sharp and well defined although minor alternating sand and clay layers at the contact zone were interpreted as a conformable contact by Commander et al. (1992). Although pollen is not preserved Commander et al. (1992) ascribed an upper Eocene age, based on their interpretation of a conformable relationship to the Wollubar Sandstone. They related the Perkolilli Shale to the Princess Royal Spongolite of the Lefroy Palaeovalley. However, Clarke (1993, 1994) correlated the upper lacustrine facies of the Lefroy and Cowan palaeovalleys, which he presumed were Oligo-Miocene, with the Perkolilli Shale. De Broekert and Sandiford (2005) stated that the Perkolilli Shale is unconformable over the Wollubar Sandstone and is probable Oligo-Miocene age although they provided no evidence other than reference to Kern and Commander (1993). De Broekert's (2002) subsequent detailed facies and stratigraphic analysis determined that the Perkolilli Shale unconformably overlies the Wollubar Sandstone, clearly indicating that the Perkolilli Shale is post-Eocene. A single pollen assemblage from the Perkolilli Shale indicated a pre-Mid Miocene age, thereby providing at least some evidence for the Oligocene to Early Miocene age estimate for the Perkolilli Shale (de Broekert, 2002).

The Roe Palaeovalley infill sequence is covered by unconsolidated colluvium, alluvium and playa deposits of presumed Quaternary age (Commander et al., 1992). Colluvial fans and broad flood-wash plains of gravel, sand and clay derived from ferricrete and underlying bedrock are the most common surficial deposits, mostly <6 metres thick. Three to six metre thick deposits of alluvial sand, silt and clay occur in the valley flats of the gently sloping and poorly defined drainage lines; these commonly interfinger with gravel-rich sediments near bedrock outcrops. Alluvial sands are poorly sorted and commonly have very fine-grained silt in the matrix. Quartz grains in these sandy deposits are also more angular than in the underlying palaeovalley sediments. Large playas along the palaeovalleys contain up to 10 metres of salty clay and silt with gypsum and have sandy gypseous lunette dunes along southern and eastern shorelines.

4.9.2.1. Roe Palaeovalley Groundwater Resources

Weathered and fractured Archaean bedrock aquifers are widespread but hydrogeologically complex in the Yilgarn, reflecting variable rock types, structural features, weathering and fracture patterns (Commander et al., 1992). Weathered bedrock consists mainly of kaolinitic clay which is mottled and gritty near granitic bedrock and clay-rich near mafic bedrock. Intergranular permeability occurs in weathered bedrock and minor volumes of groundwater are relatively widespread, although groundwater is mostly saline or hypersaline and recharge rates are low. Commander et al. (1992) reported airlift yields from investigation bores drilled in weathered bedrock of <12–22 m^3-per-day, and higher watertable levels than in the Wollubar Sandstone palaeovalley aquifer (indicating groundwater flow from bedrock towards the palaeovalleys). Chemical analyses of weathered bedrock groundwater showed similarities with groundwater in the palaeovalley aquifers, but with overall lower salinity levels. Commander et al. (1992) did not study groundwater in fresh bedrock aquifers but demonstrated connectivity between palaeochannel groundwater systems and adjacent fractured and altered basement aquifers.

The Wollubar Sandstone is the principal aquifer in the eastern Yilgarn. This palaeochannel facies forms sinuous aquifers 400–800 metres wide, underlain by weathered Archaean bedrock and mostly confined by relatively impermeable Perkolilli Shale (Commander et al., 1992). The thickness of the palaeochannel aquifer is 5–20 metres at depths of 20–30 metres below surface (Turner et al., 1994). On the basis of lithologic composition Commander et al. (1992) assumed a specific yield of 0.2 for the Wollubar Sandstone in the Roe Palaeodrainage near Kalgoorlie and reported pumping test data which determined that hydraulic conductivity increases downstream, from 20–50 m-per-day up to 30–70 m-per-day as coarser-grained sands become more abundant.

Direct recharge is restricted to palaeovalley upper reaches where the confining upper unit (Perkolilli Clay) is not present; downward vertical leakage through the confining layer is assumed to be very low, except where aquifer pressure is artificially lowered by abstraction. Some lateral recharge occurs from surrounding weathered and fractured bedrock and lateral inflow to the main palaeovalley occurs from tributaries. Where unexploited, the aquifer is essentially saturated and very little recharge can occur. Commander et al. (1992) assumed very low potential recharge due to:

- Low magnitude and intensity of rainfall;
- High evaporation rates;
- Thick vegetation cover;
- Abundant clay-rich soils; and
- Low permeability of both the weathered/fractured bedrock and the overlying confining layer.

Commander et al. (1992) were unable to quantify recharge other than by assuming that calculated discharge from salt lakes represented most of the discharge and was presumably balanced by recharge. However, their potential salt-lake discharge calculation used pan evaporation figures (2.4 m-per-year) which are known to be very much higher than true net evaporation from playas (30–170 mm-per-year) (Allison and Barnes, 1985; Ullman, 1985; Schmid, 1985; Jacobson and Jankowski, 1989; Chen, 1992). Turner et al. (1994) analysed a 55 kilometre section of the Black Flag–Gidji palaeotributary of the Roe Palaeovalley in some detail and quantified recharge by three different methods:

- **A spatial distribution model** of hydrogeochemical parameters along the palaeochannel aquifer using water and solute mass balance and ^{18}O and deuterium isotopes. This model confirmed that evaporative loss from playas is a major discharge process, accounting for 90–96% of total groundwater discharge. Net evaporation from playas was estimated from chloride profiling as 6–10 mm-per-year.
- **Groundwater residence-time estimation** from ^{14}C activity in dissolved organic carbon (DIC). The ^{14}C age of DIC increases downstream in the palaeovalley from west to east, providing clear evidence of recharge at the upstream western end and groundwater flow towards the east. Undersaturation of groundwater for calcite and dolomite, and net loss of bicarbonate ions down the valley indicated that incorporation of 'dead' carbon from carbonate mineral solution is not important. The ^{14}C data indicate a maximum flow rate of about 1 m-per-year which, when combined with average aquifer parameters (thickness of 10 metres, width of 600 metres and porosity of 0.3) provides a steady state groundwater flux of 2,000 m^3-per-year.
- **Numerical modelling** to evaluate steady-state groundwater flow in the aquifer. A three-dimensional finite difference numerical model was established by specifying constant head boundary conditions at the ends of the palaeovalley and modelling the overlying unit as a low-permeability aquifer having vertical and horizontal flow components, which allowed both the head and flux values to be calculated in the overlying saturated clays. The steady-state water balance (sum of the steady groundwater flux and evaporative discharge) was estimated from the model to be 8,900 m^3-per-year.

The steady-state groundwater balance for the Black Flag–Gidji Palaeovalley obtained by Turner et al. (1994) are summarised in Table 4.9 and compared to results from an analytical solution from Commander et al. (1992) (as reported by Turner et al., 1994).

Table 4.9: Steady-state groundwater balance for the Black Flag–Gidji Palaeovalley (data from Turner et al., 1994).

METHOD	RECHARGE ESTIMATE (10^3 m^3)	EVAPORATIVE DISCHARGE (10^3 m^3)	SUBSURFACE OUTFLOW (10^3 m^3)	RECHARGE/ ABSTRACTION	RECHARGE /STORAGE
Spatial distribution model	200-300	160-270	10-30	5-7	0.5
^{14}C activity	2	-	-	0.03	0.005
3D steady-state flow model	9	6	3	0.2	0.02
Analytical solution	8	5	3	0.2	0.02

The spatial distribution model provided the largest estimates for discharge and recharge parameters. Turner et al. (1994) considered these to be unreliable estimates as they were based on a conceptual model and not on actual physical parameters. However, this model demonstrates linkage between the solute distribution in the aquifer and the recharge, discharge and subsurface outflow components. All methods consistently demonstrated that abstraction of groundwater for mine processing (at least in the early 1990's) was considerably in excess of recharge (Table 4.9). Turner et al. (1993) indicated that leakage from overlying saturated clays induced by abstraction depressurisation provided up to 60–70% of groundwater replenishment with important implications for estimated resource volumes.

Commander et al. (1992) reported that water-level variations from bores in the Wollubar Sandstone aquifer were generally less than uncertainty and may be caused by barometric pressure variations, consistent with extremely low recharge rates. No evidence of increased recharge rates followed widespread deforestation associated with mining at the turn of the twentieth century. Commander et al. (1992) attributed recharge response to high inertia in the groundwater system compared to rapid tree regrowth. Groundwater flow in the palaeovalley aquifer occurs downstream along the palaeochannel axis with the hydraulic head lower than in the surrounding Archaean bedrock, indicating that the palaeovalleys are regional groundwater sinks, i.e., bedrock drains. The regional potentiometric surface falls west to east from about 370 metres AHD to 320 metres AHD over a distance of ~50 kilometres (Figure 4.41). The hydraulic gradient is largely controlled by the topographic gradient, and varies from 0.001 in the west to about 0.0005 in the vicinity of the downstream playas. Convergence of the steeper topographic gradient and the hydraulic gradient close to the surface near the playas results in shallow watertable levels (Turner et al., 1994). Commander et al. (1992) reported reversal of groundwater flow in part of the Wollubar/Yindarlgooda South tributary to the Roe Palaeovalley. Upstream, flow occurs from an inferred groundwater divide beneath Lake Yindarlgooda and heads towards Wollubar where the overlying Perkolilli Shale and part of the Wollubar Sandstone aquifer have been removed by erosion. Surface discharge and groundwater flow south towards Lake Lefroy.

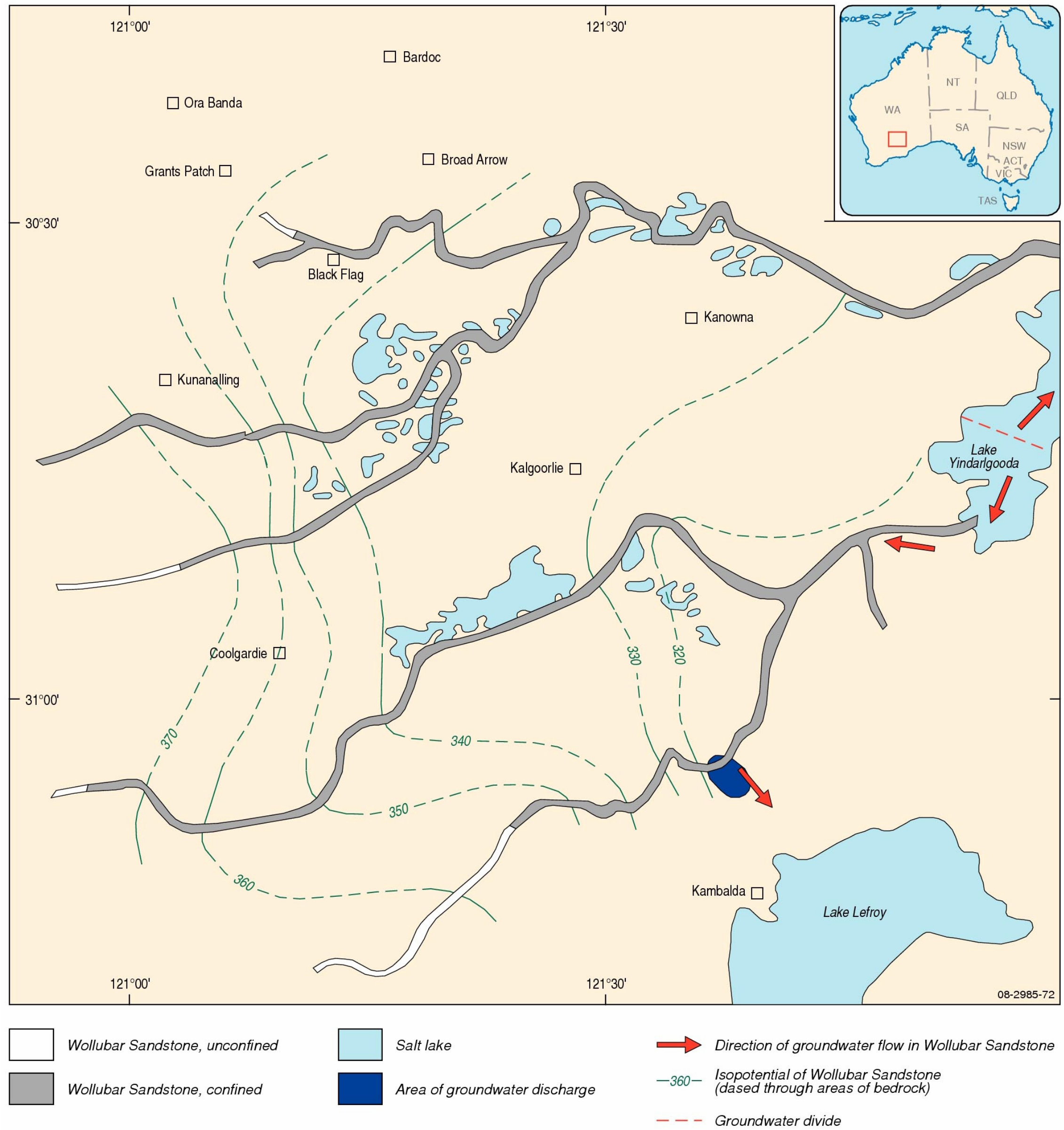


Figure 4.41: *Roe Palaeovalley potentiometric head contours for the Wollubar Sandstone palaeochannel aquifer, prior to groundwater abstraction. Figure is modified from Commander et al. (1992) (Figure 6).*

Commander et al. (1992) calculated groundwater throughflow and storage volumes for a number of sectors in the Roe Palaeovalley network (Table 4.10 and Figure 4.42). These estimates were derived from a simplified Darcy equation using measured hydraulic gradients and aquifer cross-section areas, and assumed values for hydraulic conductivity (increasing downstream as sands become coarser and cleaner) and specific yield (0.2). No adjustment was made for reduced flow due to denser and more viscous saline groundwater (likely to be 10% at 70,000 mg/L and 20% at 200,000 mg/L). Calculated throughflow rates were highly variable and ranged from 2–30 x 10^3 m^3-per-year for most sectors, with a maximum rate of 52 x 10^3 m^3-per-year for part of the Yindarlgooda North Palaeovalley where substantial lateral recharge from a tributary palaeochannel occurs. Throughflow beneath playas is very low. Groundwater resources are considered to be equivalent to aquifer storage levels because recharge rates are so low. Storage is dependent on aquifer dimensions and is variable for different sectors of the Roe Palaeodrainage network (Commander et al., 1992).

Table 4.10: Groundwater storage and throughflow in the Wollubar Sandstone aquifer of the Roe Palaeovalley. Palaeovalley and sector locations are shown in Figure 4.39. Groundwater storage volumes were calculated using a specific yield of 0.2. The values for hydraulic conductivity are adopted assuming a downstream increase as aquifer sands become coarser and cleaner. Annual throughflow is calculated from hydraulic conductivity x (potential difference/length) x area x 365.

PALAEOVALLEY SECTOR AND LENGTH	AVERAGE CROSS-SECTIONAL AREA (m^2)	STORAGE	HYDRAULIC CONDUCTIVITY (m/d)	POTENTIAL DIFFERENCE (H)	THROUGHFLOW ($10^3M^3/A$)
Black Flag (A-H): 7 kilometres	1,800	3	5	8.4	4
Black Flag (H-K): 33 kilometres	6,300	42	10	4.9	3
Kununalling (S-F): 32 kilometres	2,600	17	5	34.8	5
Kununalling (F-X): 16 kilometres	4,500	14	10	2.0	2
Bonnie Vale (J-C) : 15 kilometres	620	2	5	2.6	0
Bonnie Vale (C-I) : 10 kilometres	2,000	4	5	20.0	7
Bonnie Vale (I-G) : 8 kilometres	4,700	8	10	6.0	13
Bonnie Vale (G-X) : 21 kilometres	6,000	25	10	2.0	2
Yindarlgooda (N) : 50 kilometres	11,000	108	20	5.0	8
Yindarlgooda (X-U) : 23 kilometres	16,000	75	20	10.0	52
Hannans (R-P) : 30 kilometres	4,600	28	10	28.2	16
Hannans (P-Y) : 32 kilometres	4,500	29	10	11.0	6
Hannans (Y-L) : 30 kilometres	10,000	60	20	14.0	34
Yindarlgooda S (M-N) : 12 km	27,000	66	20	0.5	8
Yindarlgooda S (N-L): 6 kilometres	20,000	24	20	1.0	24
Wollubar (Q-E): 22 kilometres	6,100	27	5	12.1	6
Wollubar (E-Z): 34 kilometres	7,000	48	5	43.0	16
Wollubar (L-Z): 18 kilometres	12,000	43	20	6.0	30

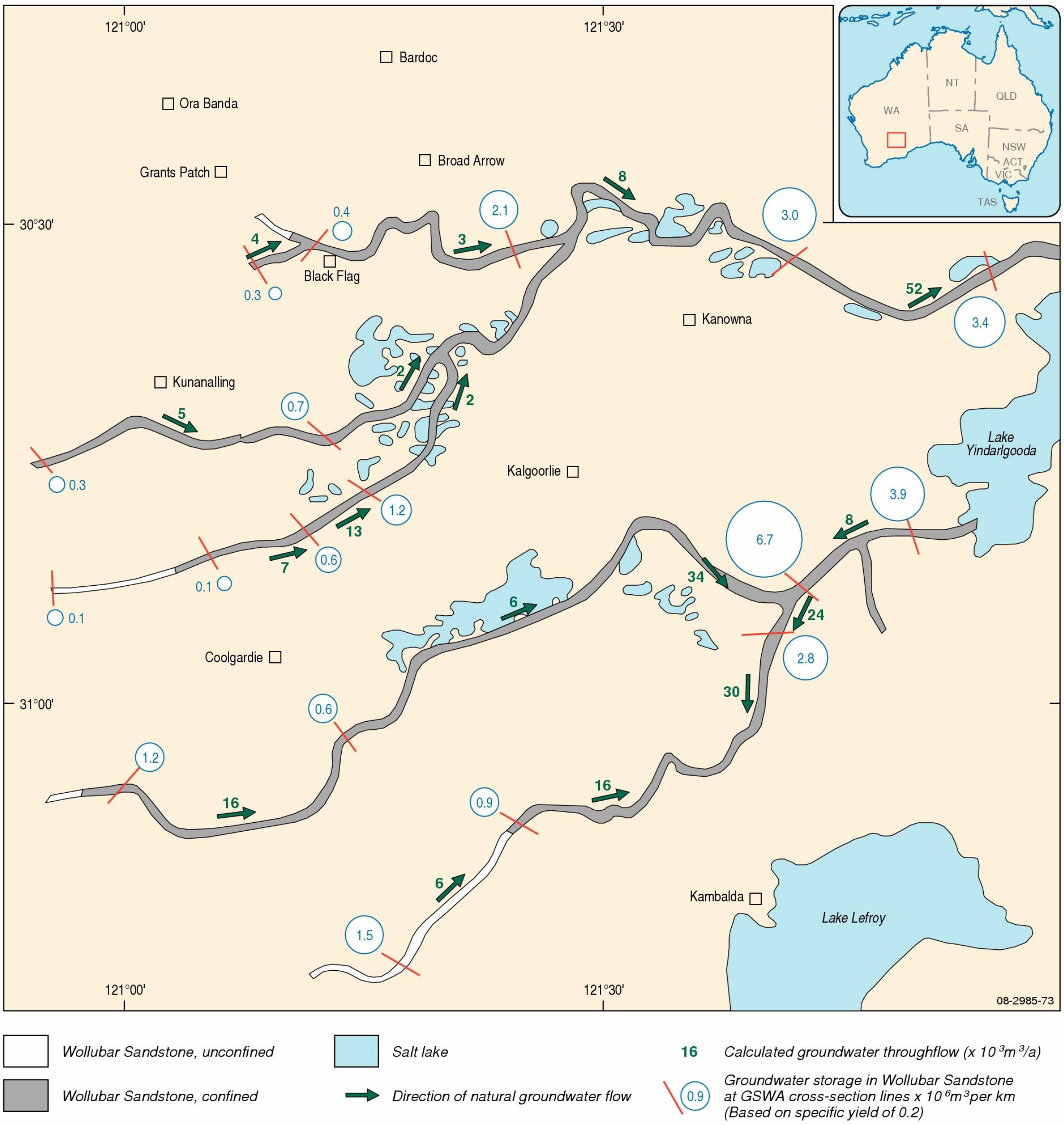


Figure 4.42: Roe Palaeovalley groundwater throughflow and storage-per-kilometre in the Wollubar Sandstone palaeochannel aquifer, prior to groundwater abstraction. Figure is modified from Commander et al. (1992) (Figure 7).

Calculations were simplified by not addressing complexities of sinuosity and aquifer thickness variations and by only considering the main palaeovalleys of the palaeodrainage network. In the study area the total groundwater storage volume in the Wollubar Sandstone was calculated as ~600 x 10^6 m^3 for 399 kilometres of the palaeovalley network, which was comparable to other estimates (Commander et al., 1992). The groundwater resources are not evenly distributed though, as the largest storage volume occurs in thicker and wider downstream palaeochannel sections. The proportion of groundwater storage which can be economically extracted is likely to be in the upper part of the aquifer which is capable of being dewatered and is highest where the palaeochannel is V-shaped and the hydraulic conductivity of the basal sands is high. Lower storage volumes occur where the palaeochannel is wide, the aquifer thin, or the hydraulic conductivity is low. The extractable proportion of groundwater was estimated to be about 80% of total storage by BHP and

AGC (1988), though this figure does not account for enhanced lateral and vertical recharge from the weathered bedrock and Perkolilli Shale which may be induced by dewatering of the Wollubar Sandstone aquifer.

4.9.2.2. Roe Palaeovalley Groundwater Quality

Detailed chemical analyses of groundwater from bores in the Roe Palaeovalley were reported by Commander et al. (1992). Relatively high-salinity groundwater was shown to occur commonly in deeper bores in the centre of palaeochannels, indicating salinity stratification of the Wollubar Sandstone aquifer. As most investigation bores were screened over the entire aquifer, the reported salinity values may reflect average salinity of the stratified aquifer or be biased by higher flow rates from specific levels. Groundwater salinity in the Roe Palaeodrainage network increases downstream (Figure 4.43), ranging from 2,800–213,000 mg/L in bores investigated by Commander et al. (1992). Groundwater salinity increases markedly in the vicinity of playas and probably exceeds 200,000 mg/L beneath most playas, although this was not fully verified by Commander et al. (1992). The ionic composition of the groundwater is dominated by sodium and chlorine, comprising ~95% of TDS (Table 4.11)

Table 4.11: Chemical composition of groundwater from the Roe Palaeovalley (data after Commander et al., 1992).

IONIC SPECIES	COMPOSITIONAL RANGE	COMMENTS
Sodium	up to 65,800 mg/L	
Chlorine	up to 115,000 mg/L	
Magnesium	500 to 8,000 mg/L	Proportional to TDS
Sulfate	2,380 to 14,100 mg/L	
Bicarbonate	Very low levels	Especially where groundwater is acidic and contains free CO_2
Iron	Up to 58 mg/L	Highly variable
Manganese	0.2 to 42 mg/L	Mostly <10 mg/L
Bromine	21 to 130 mg/L	The Br/Cl ratio is close to that of seawater in the upper part of some palaeochannels.
Strontium	3.7 to 18 mg/L	
Barium	<0.3 mg/L	
Iodide	0.06 to 0.38 ml/L	Very low I content
Copper	Below detection limits	
Chromium	Below detection limits	
Cobalt	Below detection limits	
Lithium	Below detection limits	
Nickel	Below detection limits	

Commander et al. (1992) reported that groundwater pH in the Roe Palaeodrainage system is variable (3.0–8.1) even over relatively short distances, e.g., between bores in the same transect line, and possibly at different depths within the same bore. Generally however, groundwater pH is low in the upstream palaeovalleys (3.1–4.0) and increases downstream (4.0–6.0). The most alkaline groundwater occurs in calcrete zones of the Black Flag Palaeochannel (6.0 – 7.3). Low pH levels in Yilgarn palaeovalley playas is associated with alunite formation, probably involving oxidation and hydrolysis of iron in playa-marginal mixing zones where meteoric water interacts with anoxic saline groundwater (McArthur et al., 1991). However, low pH in upper palaeovalleys away from playas requires a different explanation and may be associated with oxidation of pyrite in the palaeovalley sediments. Acidity levels can be an important factor for mine processing use where, for instance, the preferred pH for cyanide-based ore treatment is at least 9.5 (Commander et al., 1992). Thus groundwater pH must be raised significantly (with lime), which leads to precipitation of metal salts from saline water and may cause significant scaling problems. High sulfate and magnesium levels in groundwater can also led to scaling.

Figure 4.43: *Roe Palaeovalley groundwater salinity distribution in the Wollubar Sandstone palaeochannel aquifer, prior to groundwater abstraction. Figure is modified from Commander et al. 1992) (Figure 8).*

4.9.2.3. Age and Origin of Groundwater Salts

Although the large volume of salt stored in the groundwater of the Roe Palaeovalley suggests considerable accumulation time, McArthur et al. (1989) concluded that brines have evolved over tens of thousands of years rather than millions of years, because halite saturation has not occurred. From analysis of strontium and sulfur isotopes they also interpreted a cyclic marine origin for salts in shallow groundwater near salt lakes. Commander et al. (1992) calculated a salt accumulation age of

70,000 years from measured accession of marine aerosol versus total salt in groundwater storage. Commander et al. (1992; 1994) also reported ^{36}Cl ages of at least several hundred thousand years for groundwater, much older than ^{14}C ages of 8,700 and 3,600, which were thought to be caused by mixing with younger sources of carbon. Furthermore, Turner et al. (1994) reported a number of radiocarbon ages on dissolved inorganic carbon (DIC) with some downstream results at or beyond background levels (> 40,000 years).

4.9.2.4. Roe Palaeovalley Groundwater Abstraction

The Roe Palaeovalley borefields provide the most detailed Australian arid zone data on aquifer responses due to significant abstraction of palaeovalley groundwater resources (Commander et al., 1992; Johnson, 2007). Commander et al. (1992) and Turner et al. (1993) concluded that rates of groundwater abstraction in the Roe Palaeodrainage (in the early 1990's) were not sustainable with respect to down-valley recharge, despite the paucity of knowledge on recharge rates and processes. However, both studies drew attention to the unknown effects of **enhanced lateral recharge** from surrounding bedrock and overlying shale horizons, induced by the significant extraction rates of groundwater from the main palaeochannel aquifer.

Turner et al. (1996) examined the ongoing use of groundwater resources by the mining industry in the Western Australian Goldfields. One of their specific aims was to test the efficacy of induced recharge in counteracting excess groundwater abstraction over recharge, explicit in the previous assessments that concluded that palaeovalley groundwater resources were being unsustainably diminished, i.e., groundwater was effectively being mined. Turner et al. (1996) determined that the overlying aquiclude clay and shale horizons had extremely low hydraulic conductivity levels, but field slug tests suggested enhanced storage in the aquiclude and probable release of groundwater to the aquifer through cracks and fissures. They noted significant drawdown in response to abstraction and only one instance of apparent recharge response to rainfall – due to heavy rainfall from Cyclone Bobby in early 1995. Turner et al. (1996) also noted that chloride concentrations along the North Yindarlgooda palaeochannel aquifer indicated significant inflow from tributary palaeovalleys. Hydrogeochemical profiles in shallow unsaturated zones supported earlier conclusions that regional rainfall infiltration was not a significant recharge mechanism. Based on modelling of the aquifer response to pumping, Turner et al. (1996) concluded that previous estimates of the groundwater volume contributed through aquitard leakage were overestimated. They suggested that a significant proportion of the additional resource, induced by pumping of the aquifer, must be derived from undefined or unknown minor palaeochannel tributaries, such as that identified from chloride concentrations at North Yindarlgooda Palaeovalley. Research by Turner et al. (1996) resulted in a pessimistic conclusion that palaeovalley groundwater extraction for mine processing in the Roe Palaeovalley was unsustainable and would result in continued water-level decline leading to eventual storage depletion sometime between 2012 and 2022.

The apparently unsustainable nature of groundwater abstraction from the Roe Palaeovalley (as suggested by Turner et al, 1996) led to tighter regulation of palaeovalley groundwater resources in the Goldfields by the Western Australia Department of Water, via the Goldfields Groundwater Area Management Plan. This management regime allowed groundwater mining (termed 'managed depletion') in contrast to other Western Australian groundwater resources, which were allocated on an average sustainable basis (Johnson, 2007). The licensing of unsustainable abstraction levels recognised the economic importance of the gold mining operations supported by palaeovalley groundwater as well as the lack of competing uses for the saline to hypersaline resource. However, the pessimistic predictions of relatively rapid storage depletion by Turner et al. (1996) were seen as a potential limiting factor for further large-scale mining in the WA Goldfields and, as a consequence, all existing borefield operations were extensively reassessed and monitored. Additionally, as mining proceeded, ongoing groundwater abstraction was reduced by a combination of more efficient processing operations and exploitation of alternative water sources, e.g., salt lake storage of surface water runoff, and use of water obtained from open-pit dewatering and mine voids.

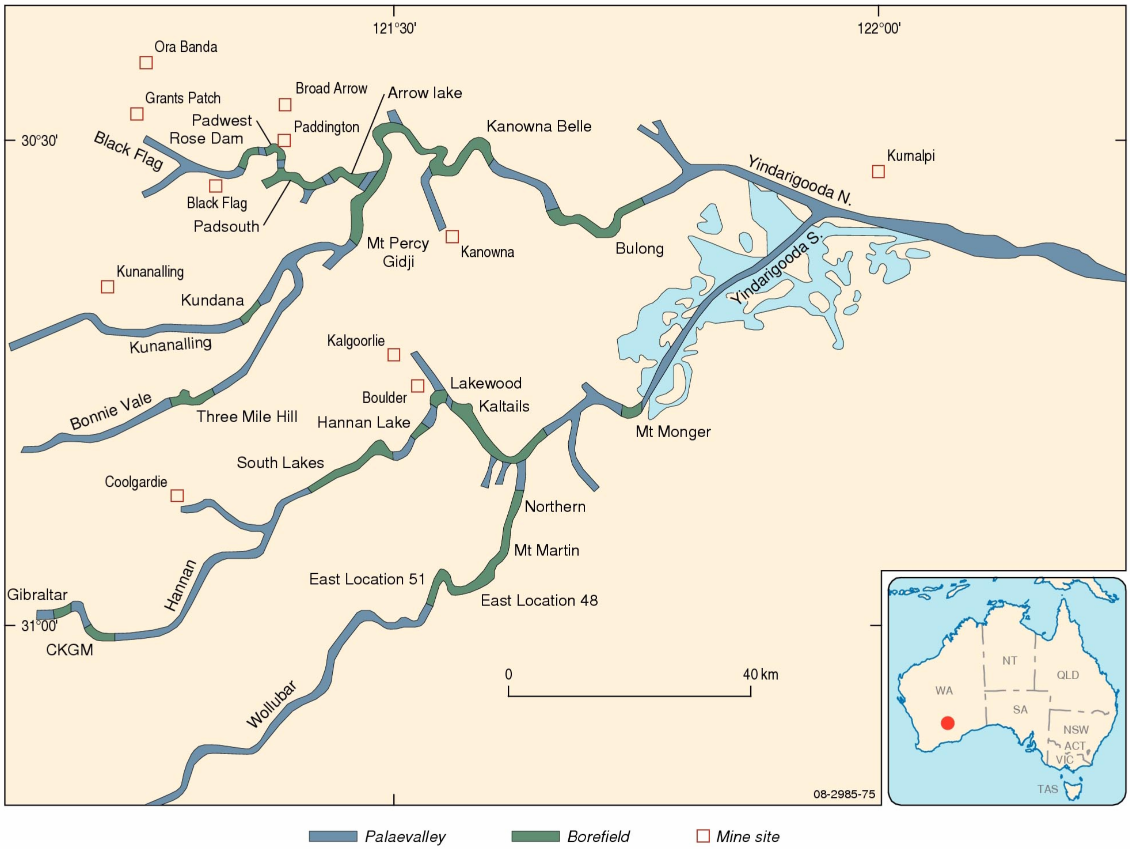


Figure 4.44: *Location map of the main borefields which abstract groundwater from the Wollubar aquifer of the Roe Palaeovalley. Figure is modified from Johnson (2007) (Figure 1).*

Johnson (2007) documented the response of the Roe Palaeochannel aquifer to groundwater abstraction, based on bore hydrograph data from 1990–2001. Groundwater abstraction from this aquifer began in 1984, peaked through the early 1990's and declined after 1997. From the Roe Palaeovalley Johnson (2007) presented data from ten borefields in the Yindarlgooda North Palaeovalley (plus the Black Flag, Kunanalling and Bonnie Vale tributaries) and from eleven borefields in the Yindarlgooda South Palaeovalley (plus the Hannan and Wollubar tributaries) (Figure 4.44). In combination, these borefields have >80 production bores and 50 observation bores along 110 kilometres of the Roe Palaeovalley (which has a total combined length of ~400 kilometres). Total abstraction volume from 1985–1996 was about100 GL, although the average rate in the mid-1990's was ~10 GL-per-year (Figure 4.45). In 1996, for instance, abstraction was 12.4 GL compared to a licensed allocation of 30.5 GL. In general, bore hydrographs show direct groundwater response to extraction but negligible response to significant rainfall events, although a few bores have unusual hydrograph trends that may be attributable to indirect recharge.

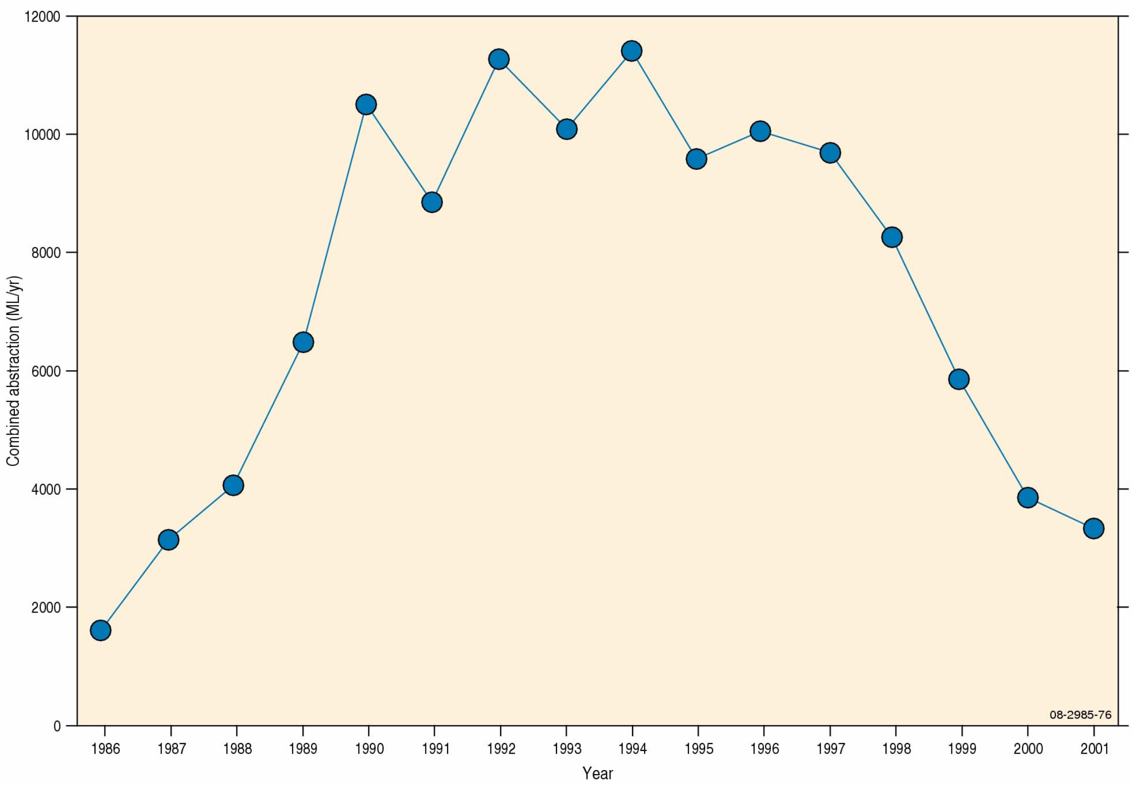


Figure 4.45: *Combined yearly abstraction rates for all borefields on the Roe Palaeovalley between 1986 and 2001. Note the peak usage time in the early- to mid-1990's. Figure is modified from Johnson (2007) (Figure 4).*

Johnson (2007) highlighted the importance of the transition from confined to unconfined conditions as a result of groundwater abstraction (Figure 4.46). Under confined conditions groundwater storage in the aquifer is virtually unchanged by abstraction, with groundwater produced from a combination of aquifer compression and vertical and lateral leakage. However, in places where the aquifer is unconfined, groundwater is produced dominantly by depleting aquifer storage. The initial aquifer condition effectively controls the extent and rate of groundwater drawdown, the establishment of quasi steady-state conditions and the nature of water-level recovery in response to abstraction. Transition between confined and unconfined conditions results in three main water level responses and rates of change within the aquifer (Johnson et al., 2007):

- Aquifers that maintain confined conditions experience rapid drawdown to a quasi steady-state level and rapid water level recovery (Figure 4.47);
- Aquifers that change from confined to unconfined conditions experience rapid drawdown to the top of the aquifer and quasi steady-state conditions with slow recovery until confined conditions are re-established (Figure 4.48); and
- Initially unconfined aquifers experience slow drawdown to a quasi steady-state and slow recovery (Figure 4.49).

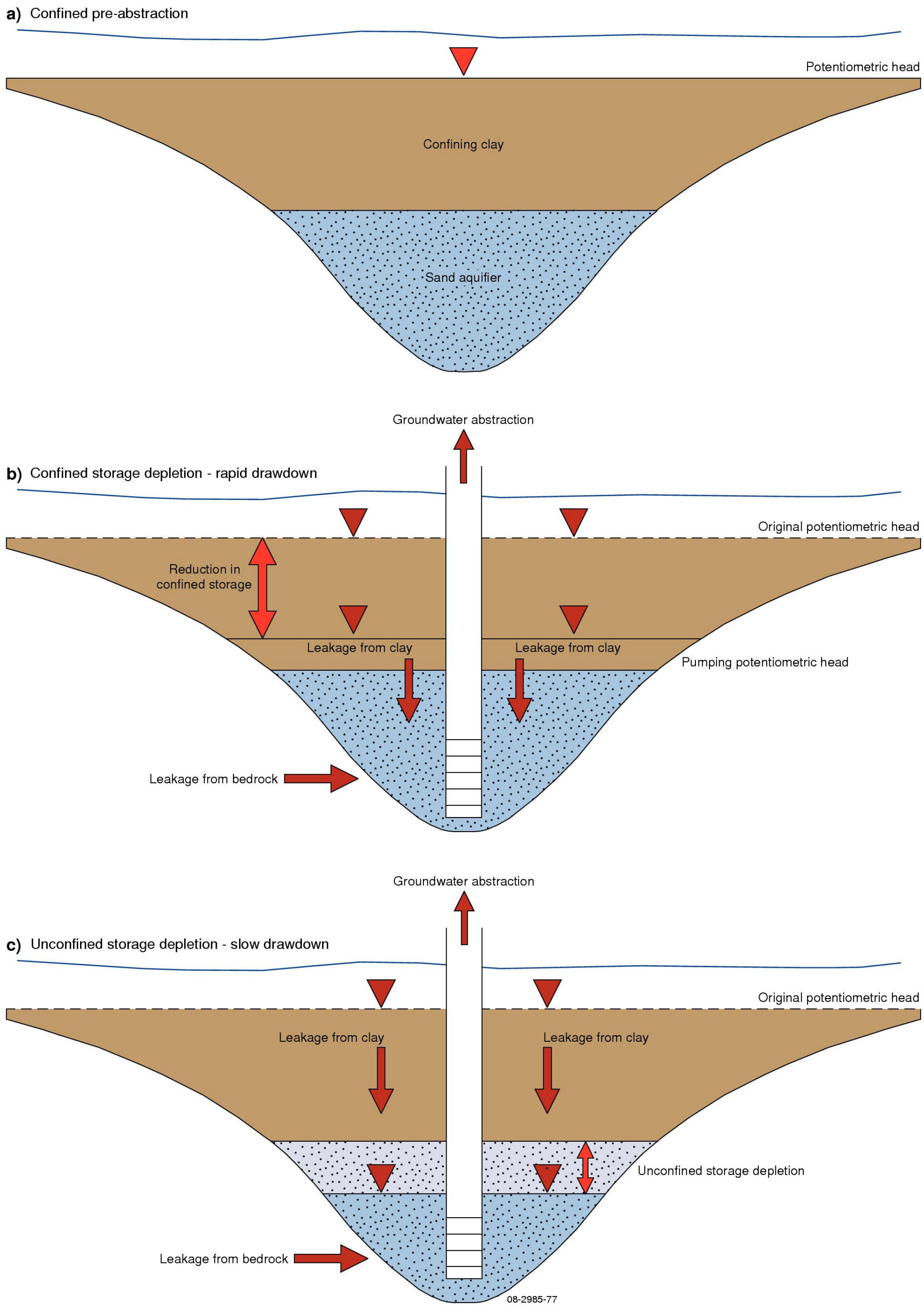


Figure 4.46: *Diagrammatic cross-sections demonstrating the transition from confined to unconfined aquifer conditions caused by groundwater abstraction from borefields in the Wollubar Sandstone aquifer of the Roe Palaeovalley. Figure is modified from Johnson (2007) (Figure 3).*

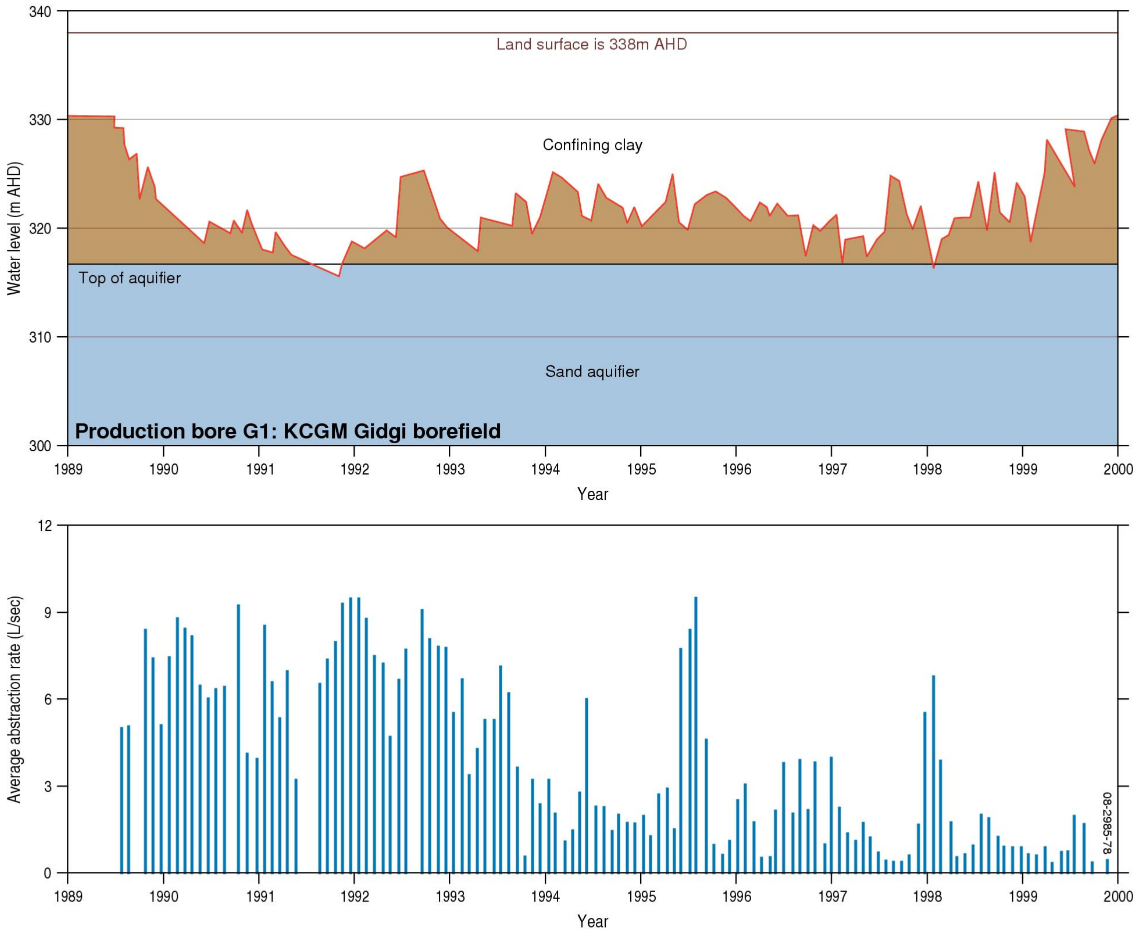


Figure 4.47: *Groundwater abstraction rates and corresponding water-level variations from Bore G1 in the Gidji Borefield of the Roe Palaeovalley between 1989 and 2000. Rapid water-level drawdown followed initial groundwater abstraction before quasi steady-state conditions were subsequently maintained. This response is typical of confined aquifer conditions maintained throughout the abstraction period. Figure is modified from Johnson (2007) (Figure 7).*

Initial groundwater drawdown levels after two or three years of abstraction from the Roe Palaeochannel aquifers were 5–10 metres. The drawdown rate was estimated at 3–5 metres-per-year for confined aquifers and 1–2 metres-per-year for unconfined aquifers (Johnson, 2007). After initial drawdown response, the groundwater level in the aquifer enters quasi steady-state equilibrium between abstraction and inflow. Inflow is sourced from groundwater throughflow and vertical and lateral leakage boosted by indirect recharge. Extended periods of quasi steady-state conditions occur, commonly near the top of the aquifer, although this depends on the original watertable level, the confinement conditions and the abstraction rate. Even in places where drawdown has induced unconfined conditions, all bores have continued to remain in production with their saturated aquifer thicknesses (10–20 metres) maintained (Johnson, 2007). Reduced abstraction rates after the mid-1990's (Figure 4.45) resulted in water-level recovery at the average rate of 2–3 metres-per-year in confined aquifers and 0.5 metres-per-year in unconfined aquifers. Water-level recovery in confined aquifers is significant and has returned to pre-abstraction levels in some borefields. Recovery has also occurred in some confined borefields, e.g., at Mt Percy, even though full production may have continued at neighbouring borefields. This indicates that throughflow is not the dominant method of groundwater inflow. Recovery occurs more slowly in unconfined aquifers (Johnson, 2007).

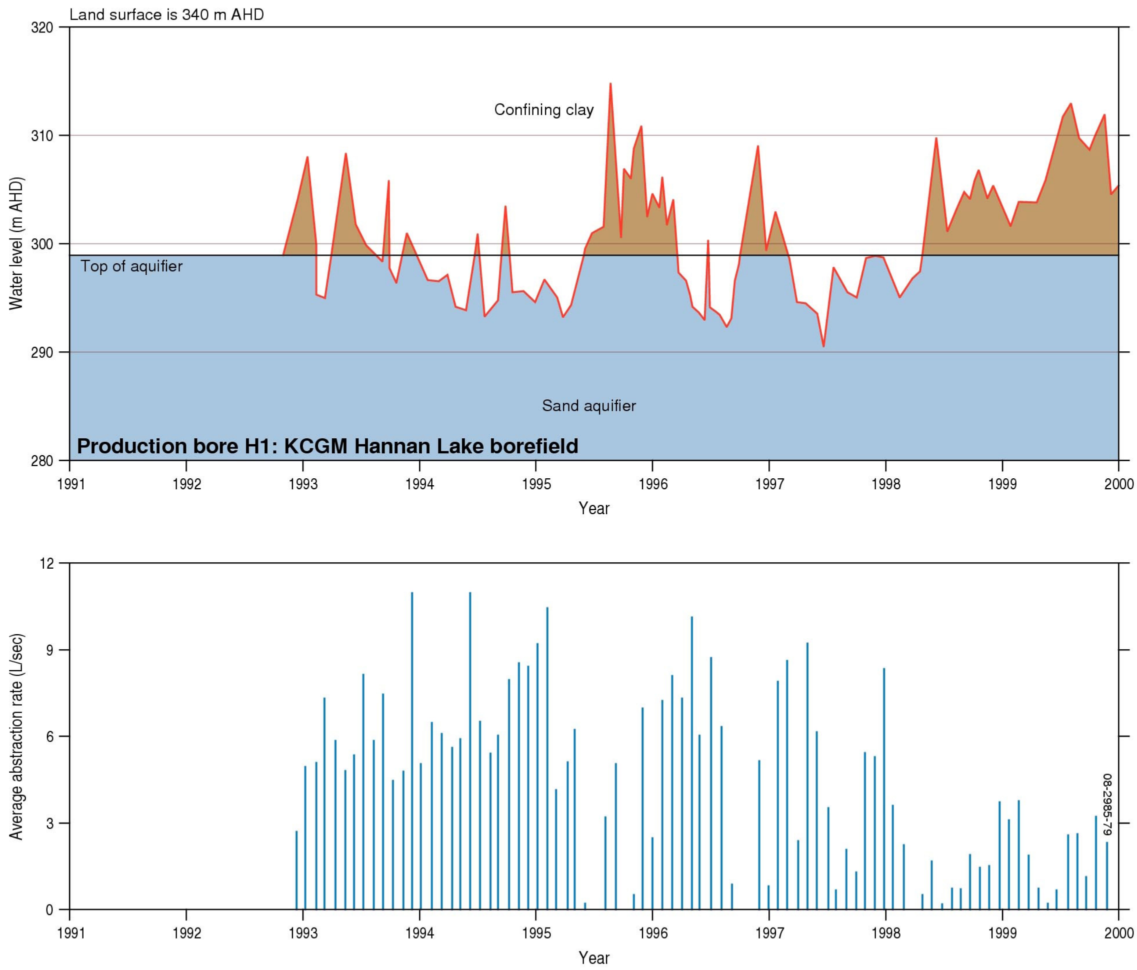


Figure 4.48: *Groundwater abstraction rate and corresponding water-level variation from Bore H1 (KCGM Hannan Lake Borefield) in the Roe Palaeovalley before 1993 and 2000. The water-level curve shown here demonstrates transition from confined to unconfined aquifer conditions. Figure is modified from Johnson (2007) (Figure 8).*

Groundwater pumping at Kaltails Borefield from 1990–1999 extracted 18.4 GL at an average rate of 1.8 GL-per-year. At the height of production this borefield consisted of 15 bores spaced at 1,200 metre intervals along 17 kilometres of the Yindarlgooda South Palaeovalley (Figure 4.44). Initial water-level drawdown of 2.9 metres produced unconfined conditions with the water-level at or up to 5 metres below the top of the aquifer. Water-levels fluctuated only a few metres between 1991 and 1999, indicating quasi steady-state conditions. Since closure of the borefield in September 1999 slow recovery of the water-level has occurred (~0.5–1 metres-per-year); the aquifer across most of the borefield remained unconfined in 2003, with minor drawdown periods correlated to enhanced abstraction from the neighbouring Lakewood Borefield. Continued monitoring of water-level recovery in Kaltails borefield will elucidate the timing and nature of the transition from unconfined to confined conditions within this palaeochannel aquifer (Johnson, 2007).

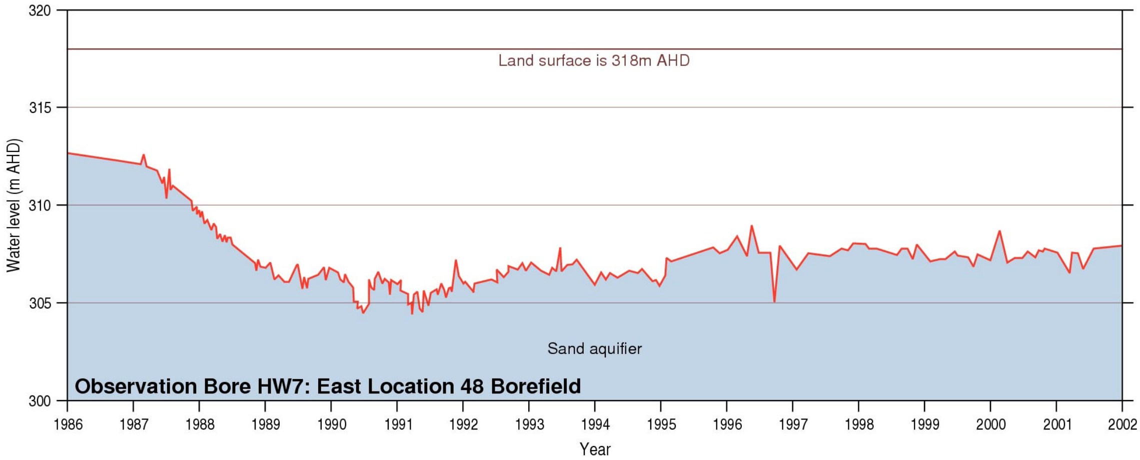


Figure 4.49: *Water-level variations for Observation Bore HW7 (East Location 48 Borefield) in the Roe Palaeovalley between 1986 and 2001. This curve demonstrates a typical unconfined aquifer response to prolonged groundwater abstraction from the Wollubar Sandstone palaeochannel aquifer. Note that no confining clay layer is present at this bore. Figure is modified from Johnson (2007) (Figure 9).*

Initial hydrogeological study of the Roe Palaeovalley (Commander et al., 1992; Turner et al., 1994) determined that direct recharge to the palaeochannel aquifers is negligible (Figure 4.50). For example, bore hydrographs recorded no direct water-level response to extreme rainfall events (Johnson, 2007). However, the continuation of steady-state conditions and recovery of the aquifer water-level during abstraction requires inflow to respectively match or exceed abstraction. Inflow must occur by throughflow or leakage from surrounding rocks, with the latter likely to be dominant as indicated by the minimal effects on water-levels due to abstraction in neighbouring borefields. Variations in the water and salinity level of some palaeochannel aquifer bores may indicate that indirect recharge from leakage occurs (Johnson, 2007). Monitoring bores in weathered basement rocks adjacent to palaeovalleys show clear evidence of recharge from high-magnitude rainfall events; Johnson (2007) suggested a model of indirect recharge to palaeochannel aquifers by downward movement through the weathered profile and lateral leakage to the palaeochannel aquifer. This process is likely to be enhanced by aquifer depressurisation due to abstraction. Wharton (2002) suggested an important recharge role for flooded playas and Johnson (2007) suggested that this was probably via leakage from the playas to the weathered bedrock as the playas are generally offset from, or extend well outside of, the main palaeovalley tracts.

Groundwater abstraction has generally had minimal impact on palaeovalley aquifer salinity. Johnson (2007) suggested that some bores with long-term trends showing salinity increasing with abstraction may indicate enhanced indirect recharge of hypersaline water sourced from playas. Bores with long-term reducing salinity levels indicate enhanced throughflow from nearby tributary palaeovalleys which contain fresher groundwater.

In summary, detailed monitoring of long-term Roe Palaeovalley water-levels in response to abstraction (Johnson, 2007) has demonstrated that groundwater resources are considerably more robust than predicted by earlier studies (Commander et al., 1992; Turner et al., 1994; Turner et al., 1996). Most borefields have maintained steady-state conditions which indicate sustainable balance between groundwater inflow and abstraction. This is further confirmed by subsequent recovery of groundwater-levels with reduced abstraction rates. Steady-state conditions for major borefields in the Roe Palaeovalley are shown in Table 4.12. Johnson (2007) suggested that these data indicate a sustainable yield of at least 10 GL-per-year for the 110 kilometres of palaeovalley strike-length represented by the existing borefields. When extrapolated across the entire 400 kilometre length of the Roe Palaeovalley in the eastern Yilgarn, Johnson (2007) suggested a conservative sustainable yield estimate of 35 GL-per-year. On this basis, Johnson (2007) recommended that allocation of Roe Palaeovalley groundwater be redefined from the former regime of managed depletion to an average sustainable basis.

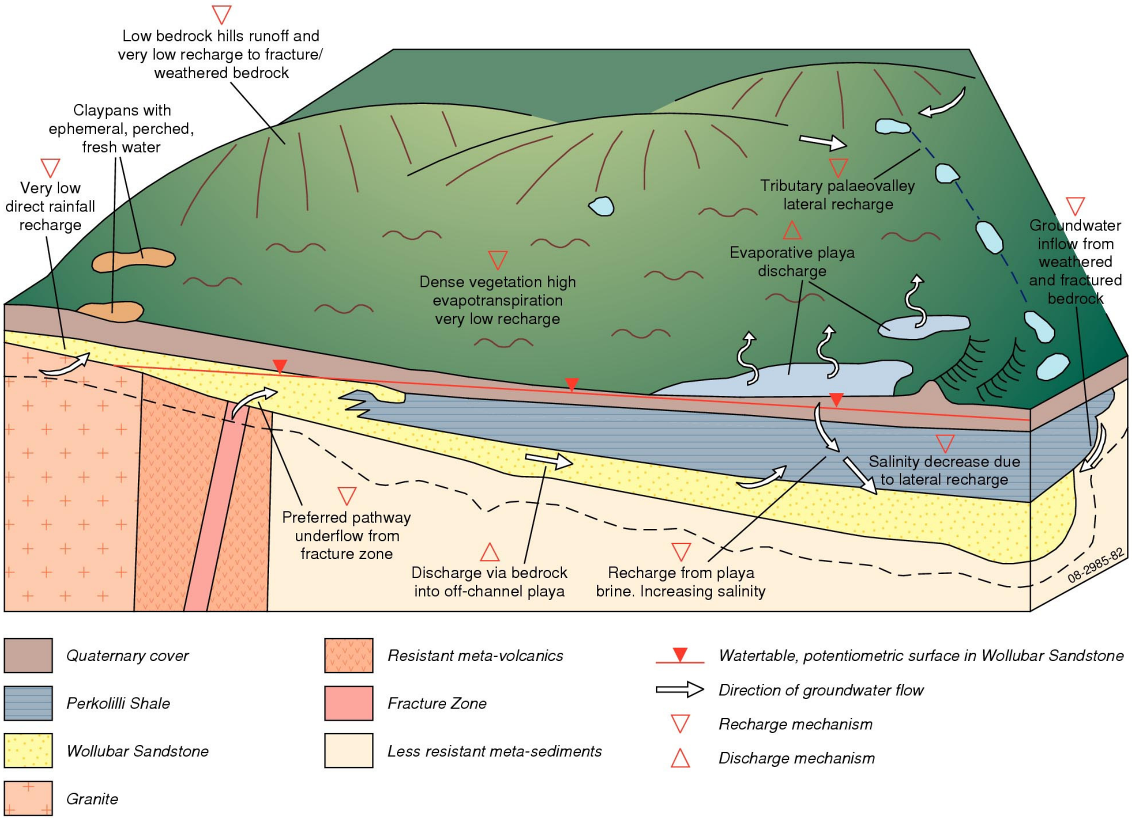


Figure 4.50: *Schematic block diagram showing the conceptual relationships of palaeovalley groundwater hydrodynamic processes based on detailed study of the Roe Palaeovalley in the eastern Yilgarn. Direct rainfall recharge of the Wollubar Sandstone aquifer is minimal. Figure is modified from Commander et al. (1992) (Figure 4).*

Table 4.12: Period of steady-state aquifer water levels and associated groundwater abstraction rates in Roe Palaeovalley major borefields (after Johnson, 2007).

BOREFIELD NAME	PERIOD OF STEADY STATE CONDITIONS	AVERAGE ANNUAL ABSTRACTION (GL/YEAR)
Kaltails	1993 - 1998	1.735
New Celebration	1992 - 1997	1.145
South Lake & Hannan Lake	1993 - 1996	1.580
Gidji	1994 - 1998	2.520
Mountt Percy	1993 - 1998	0.585
Lakewood	1990 - 2001	0.355
Kanowna Belle	1995 - 1997	0.980
Jubilee	1999 – 2001	0.190
Paddington	1996 - 1998	0.860
Total		**9.090**

4.9.3. Other Eastern Yilgarn Palaeovalleys

Eastern Yilgarn palaeovalleys situated north of the Roe Palaeovalley include the Rebecca, Raeside and Carey palaeovalleys (Figure 4.51). Johnson et al. (1999) examined the stratigraphic architecture of the Raeside and Carey palaeovalleys and found a similar profile to the Roe, with basal fluvial sands (Wollubar Sandstone equivalent) overlain by lacustrine clays (Perkolilli Shale equivalent) (Figure 4.52). However, unlike the Roe Palaeovalley sequence which has a relatively thin Quaternary surficial cover, Johnson et al. (1999) reported up to 60 metres of alluvial sediments overlying the Perkolilli Shale equivalent – these may be Pliocene or Quaternary age. Johnson et al. (1999) also showed that abundant secondary groundwater calcrete occurs, especially in the Raeside Palaeochannel where calcite massively replaces older sediments at the margins of playas and locally in the main palaeovalleys. Solution features are common in the calcrete zones, particularly associated with the modern watertable.

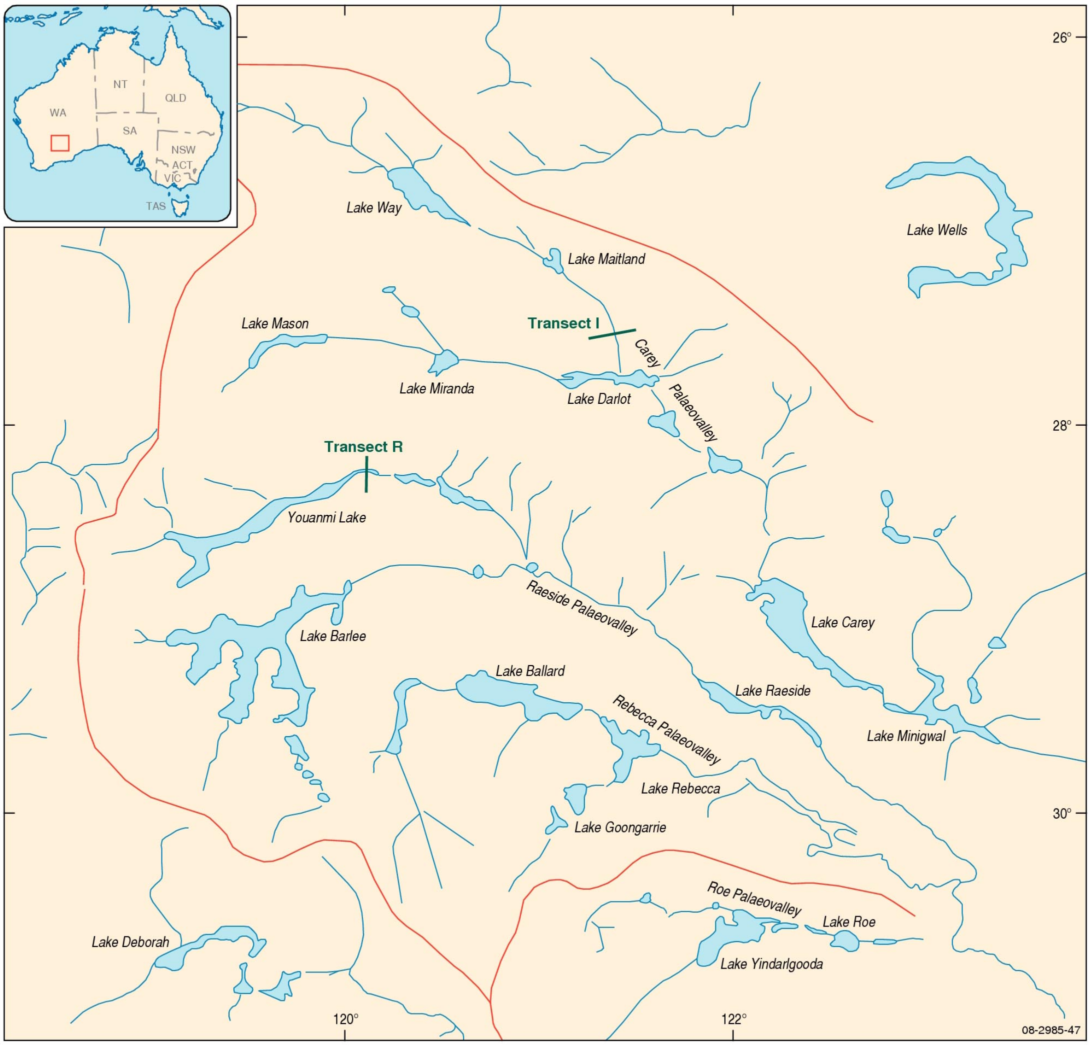


__Figure 4.51:__ Regional map of the north-eastern Yilgarn Craton showing the location of the Rebecca, Raeside and Carey Palaeovalley systems to the north of the Roe Palaeovalley. Note the abundance of salt lakes developed along the line of each palaeovalley system. Drilling transect lines I and R across the palaeovalleys mark the location of the interpreted cross-sections shown in Figure 4.52. Figure is modified from Johnson et al. (1999).

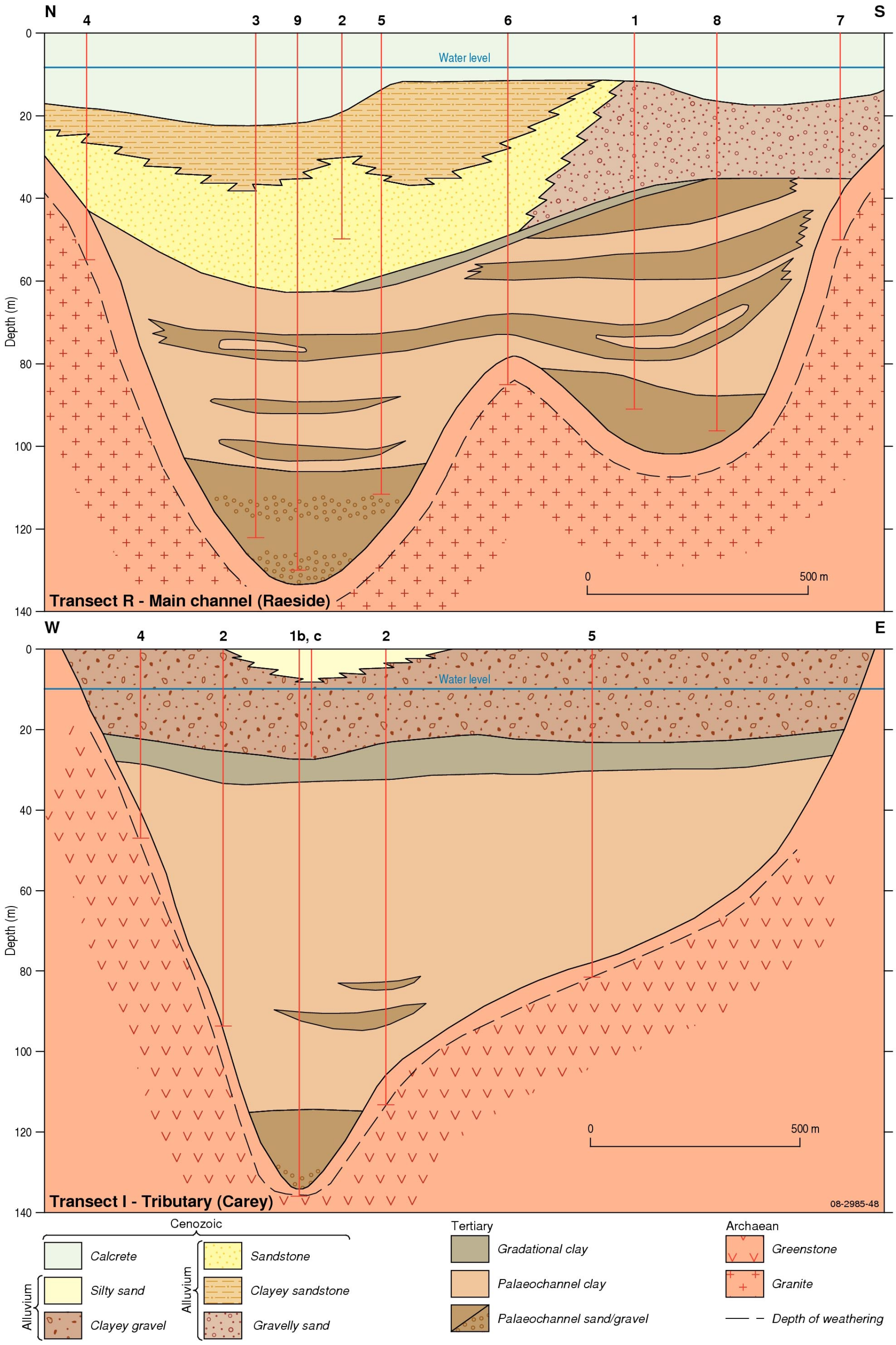


Figure 4.52: *Interpreted stratigraphic cross-sections through parts of the Raeside (Line I) and Carey (Line R) palaeovalleys (line locations shown on Figure 4.51). These palaeovalleys contain significant thicknesses of Late Cenozoic alluvial and colluvial sediments which overlie the older (Tertiary) palaeochannel sand and clay horizons in the deeper parts of the incised valley. Figure is modified from Johnson et al. (1999).*

4.9.3.1 Other Eastern Yilgarn Palaeovalley Groundwater

Commander et al. (1992) suggested that the Rebecca and Lefroy palaeovalleys were likely to contain similar quantity and quality of groundwater resources to the Roe Palaeovalley. Johnson et al. (1999) reported detailed groundwater investigations of the Raeside and Carey palaeovalleys in the north-eastern Yilgarn, involving geophysical surveys and drilling transects. The geological setting is similar to that of the Roe Palaeovalley with palaeodrainage networks eroded into weathered Archaean bedrock and filled with basal Eocene fluvial channel sands, equivalent to the Wollubar sandstone, overlain by lacustrine clays. Johnson et al. (1999) described the boundary between the channel infill units as gradational, and the channel infill sequence is overlain by Neogene to Quaternary alluvium and colluvium which is locally replaced by calcrete. Calcrete is generally calcite-rich rather than dolomitic. Most calcrete zones have formed by replacement or displacement of colluvial or alluvial sediments; carbonate minerals have precipitated directly from carbonate-saturated groundwater, with most carbonate presumably derived from the alteration and decomposition of greenstone bedrock. Calcrete deposits occur commonly at the margins of salt lakes and in the main palaeovalley sections, and most are <10 metres thick.

As for the Roe Palaeovalley (Commander et al., 1992; Kern and Commander, 1993), aquifers in the vicinity of the Raeside and Carey palaeovalleys include fractured and weathered Archaean bedrock and palaeovalley sediments. Groundwater characteristics in the palaeovalley channel sand aquifer are similar to the Roe Palaeovalley, e.g., very low recharge from rainfall in upstream reaches, and groundwater flow occurs under gravity with generally low hydraulic gradients directed towards playas. A significant hydrogeological difference between the Raeside and Carey palaeovalleys and the Roe Palaeovalley is the presence of important aquifers overlying the typical palaeovalley infill sequence. These near-surface aquifers have good primary porosity (but low permeability) developed in various colluvial and alluvial sediments, and secondary solution-derived porosity and high permeability in calcrete zones.

Johnson et al. (1999) clearly demonstrated the importance of palaeovalley aquifers compared to bedrock aquifers in the northern Yilgarn (Table 4.13). In particular, the near-surface alluvial sediments contain significant volumes of fresh to brackish groundwater compared to the dominantly saline and hypersaline water in basal palaeochannel sand aquifers. Renewable groundwater resources are low for all aquifer types, reflecting the extremely low recharge rates – especially for the palaeochannel sands. Storage estimates for the alluvial aquifer were calculated from the areal extent of the saturated zone using a specific yield of 0.05. However, although the surficial sediment horizons contain significant quantities of low salinity water, they cannot be directly tapped due to low aquifer permeability. Hence, these aquifers only provide useable groundwater via leakage into underlying palaeochannel sand and bedrock aquifers.

Table 4.13: The volume of groundwater stored in various aquifer systems on the basis of different salinity levels in the vicinity of the Raeside and Carey palaeovalleys (data from Johnson et al., 1999).

AQUIFER TYPE	0–1,000 (mg/L)	1,000–3,000 (mg/L)	3,000–14,000 (mg/L)	>14,000 (mg/L)	TOTAL STORAGE (GL)	RENEWABLE RESOURCES (GL)	ASSUMED SPECIFIC YIELD
Alluvial	1,026	3,845	4,790	1,639	11,300	43	0.05
Calcrete	66	215	561	47	889	30	0.05-0.25
Palaeovalley basal sand	46	97	214	3,002	3,359	?	0.2
Bedrock	321	283	187	65	856	27	0.001 to 0.05

Due to their karstic nature, calcrete aquifers have variable specific yield (0.05–0.25), commonly high at the watertable. Basal palaeochannel sands provide the most significant and readily accessible groundwater reserves within a mostly continuous and confined aquifer system. They typically have an average hydraulic conductivity of 10 metres-per-day, although most groundwater reserves are significantly saline.

Groundwater salinity in the main aquifers shown in Table 4.13 is partly controlled by topographic gradients, and there is a regional trend of increasing salinity parallel to the direction of flow towards the south-west where recharge rates are relatively low. Potable groundwater (<1,000 mg/L) occurs in bedrock aquifers on catchment divides and in the upper reaches of palaeovalleys. Groundwater salinity within the Raeside and Carey palaeochannel sand aquifer is fresh to brackish (1,000–3,000 mg/l) in tributaries, but becomes considerably saline in the main palaeovalley channel (up to 238,000 mg/L) and tends to increase downstream towards playa discharge zones. Groundwater salinity levels are stratified in some palaeochannel sand aquifers and lower salinity water occurs near palaeochannel margins due to lateral inflow from tributaries and bedrock aquifers. As in the Roe Palaeovalley, the ionic composition of groundwater in the Raeside and Carey palaeovalleys is dominated by sodium and chlorine with significant (though variable) levels of calcium, magnesium and sulfate. The major contrast to the Roe Palaeovalley is the absence of low pH groundwater, presumably reflecting the abundance of secondary calcrete in the Raeside and Carey palaeovalleys. Nitrate levels in groundwater tend to be consistently higher in the Raeside and Carey systems than they are in the Roe Palaeovalley.

4.10. MUSGRAVE PROVINCE AND OFFICER BASIN

The Musgrave Province occurs across north-west South Australia, south-west Northern Territory and the western part of Western Australia (Figure 4.53). It comprises very high-grade metamorphic rocks and protoliths of Mesoproterozoic age which have been intruded by abundant mafic and felsic rocks (Major and Conor, 1993; Conor et al., 2006). The Musgrave Province is bounded by Neoproterozoic to Devonian intracratonic basins which were probably linked with the Officer Basin and the Amadeus Basin (Figure 4.53). At its southern boundary the Musgrave Block is unconformably overlain by sedimentary rocks of the Officer Basin but the boundary is complicated by overthrusting of the basement. Further south, the Officer Basin is unconformably overlain by marine and terrestrial sediments of the Cenozoic Eucla Basin (Preiss et al., 2002). A large palaeodrainage network fed into the Eucla basin in the early Cenozoic; this included the drainage systems of the eastern Yilgarn in the west, the Musgrave Province in the north, and the Gawler Craton in the east. Palaeovalleys are incised into the bedrock terrane of the Musgrave Province and the overlying Officer Basin sedimentary rocks, and have overlying Quaternary calcrete, aeolian sand and playa deposits (Zang and Stoian, 2006).

The central palaeovalleys of the former Eucla Basin network described above occur in the vicinity of the Western Australia–South Australia border, rising in the western and southern margins of the Musgrave Province and traversing the Gibson and/or Great Victoria Deserts across the Officer Basin. These palaeovalleys comprise the Throssel, Baker, Kadgo and Waigen palaeovalleys in Western Australia, the Serpentine Lakes Palaeovalley straddling the border and the Noorina, Lindsay, Merramangye and Tallaringa palaeovalleys in South Australia. Away from the bedrock ranges this palaeodrainage network is largely obscured by surficial cover, especially the dunes of the Great Victoria Desert, although it has been largely mapped in Western Australia (Beard, 1973, 2002) and South Australia (Statham-Lee, 1994, 1995; Hou et al., 2007). The upper reaches of the Western Australian palaeovalleys which rise and trend west of the Musgrave Province (Throssel, Baker and Kadgo palaeovalleys) have been extensively diverted and disrupted by post-Eocene tectonic activity which has resulted in conflicting interpretations of the palaeodrainage network (Beard, 1973;

Bunting et al., 1973; van der Graaff et al., 1977). Beard (2002) investigated these inconsistencies in some detail using high-quality topographic information and has provided probably the best interpretation. The Throssel Palaeovalley was beheaded by major tectonic disruption with loss of the section above Cobb Lake (Beard, 2002, Sandiford et al., 2007). This resulted in the formation of an internally closed drainage basin from the northern portion of the original Throssel Palaeovalley.

Figure 4.53: *Regional map of central-southern Australia showing the major geological terranes of the region. The various palaeovalley systems which rise in the Musgrave Province and flow southwards across the Officer Basin towards the Eucla Basin are also identified. Palaeovalley locations sourced from Beard (1973) and Hou et al. (2007).*

In contrast to palaeovalleys of the east Yilgarn and Gawler Craton, the central palaeovalleys draining south and east of the Musgrave Province and across the Officer Basin are poorly understood. The South Australian part of this region is generally known as the Anangu Pitjantjatjara and Yankunytjatjara (APY) Lands and is contiguous with Aboriginal reserves across the Western Australian and Northern Territory borders. In the APY lands, geological exploration has focussed on mineral resources in the bedrock terrane of the Musgrave Ranges and oil and gas in the Officer Basin. The only information on palaeovalley stratigraphy and groundwater resources has come from groundwater resource studies for indigenous communities, road and rail construction, mining and oil exploration and government infrastructure (e.g., the Maralinga atomic test site and Giles meteorological station). Miller (1967) reviewed early groundwater investigations in the Musgrave Province, which commenced in 1955 with drilling by the South Australian Department of Mines (SADM) to support nickel exploration. Other surveys and drilling (by SADM) for the Giles meteorological station and various Aboriginal communities and pastoral enterprises continued through the later 1950–1960's (Johnson, 1956; O'Driscoll, 1956; Miller, 1967). With the spread of indigenous communities and outstations through APY lands, South Australian Government hydrogeologists in various agencies have continued community water supply surveys, drilling and bore monitoring from the 1970's to the present day, e.g., Nelson (1974), Stadter et al. (1979), Read, (1986; 1989; 1990; 1991), Dodds (1996; 1997), Tewksbury and Dodds (1996; 1997), Clarke (2000), Sampson and Dodds (2000), Dodds and Sampson (2000; 2001), Clarke and Dodds (2001). Due to poor exposure and limited subsurface information, bores have frequently been unsuccessful and geophysical techniques, especially transient electromagnetic (TEM) surveys, have been increasingly used to improve stratigraphic and groundwater definition but with generally limited success (Nelson, 1974; Dodds, 1996, 1997; Clarke, 2000; Tewksbury and Dodds, 1996, 1997).

The palaeodrainage network across the Officer Basin was interpreted from pre-dawn thermal imagery obtained from the NOAA–AVHRR satellite system (National Oceanic and Atmospheric Administration–Advanced Very High resolution Radiometer) (Statham-Lee, 1995; 1994). This work was published at 1-million scale as part of the 'Geological Atlas of the Officer Basin, South Australia' (Lindsay, 1995). In the NOAA–AVHRR imagery the palaeovalleys appear dark because they have lower thermal inertia and are cooler than surrounding basin rocks. The 1.1 kilometre pixel resolution of the NOAA–AVHRR satellite data restricts recognition to trunk and major palaeovalley tributaries, but still allows mapping of the palaeodrainage network in considerable detail (Statham-Lee, 1995).

Limited and slightly contradictory stratigraphic information is available on the nature of the sedimentary infill for palaeovalleys in the Musgrave region. Zang and Stoian (2006) identified two palaeovalley units – Eocene fluvial Pidinga Formation and Miocene to Pliocene lacustrine Garford Formation – both of which are well known from nearby palaeovalleys at the margin of the Gawler Craton and Eucla Basin. The Pidinga Formation commonly comprises up to 50 metres of variable sediment types, including green-grey, poorly to moderately sorted, fine quartz sand, granule conglomerate, fine- to medium-grained quartz sand, silt with minor clay, carbonaceous silt, and lignite. Coarser-grained carbonaceous and lignitic sediments occur in palaeochannels and finer-grained overbank sediments on palaeo-flood plains. Pollen preserved *in situ* implies that drainage development was initiated in the Early Eocene (Hou et al., 2006), with sedimentation ongoing to the Late Eocene, perhaps extending into the Early Oligocene (Zang and Stoian, 2006). The Garford Formation outcrops sporadically in some palaeovalleys, such as the low playa-marginal cliff sections of the Merramangye Palaeovalley. It consists of predominantly lacustrine and floodplain deposits of pale green-grey and dark red-brown, poorly to moderately sorted, very fine to coarse sand, silt and clay. Some fluvial channel deposits occur at the base. The age of the Garford Formation is probably Mid Miocene to Early Pliocene. As part of the Geological Atlas of the Officer Basin, South

Australia, Lau et al. (1995) mapped the regional groundwater systems at 1 million-scale. They identified Garford Formation sediments and the Mangatitja Limestone – lacustrine dolomite, clay, silt and sand – as the main stratigraphic units in palaeovalleys which trend southwards from the Musgrave Province across the Officer Basin to the Eucla Basin. Dodds (1997) and Tewksbury and Dodds (1996) identified palaeovalley infill sediments at Oak Valley as Pidinga Formation (lignitic sand and clay with discontinuous coarse sand and gravel channel deposits) overlain by Hampton Sandstone (partially silicified fine- to medium-grained sand).

Palaeovalleys are overlain by sand dunes of the Great Victoria Desert, composed of undifferentiated orange quartz sand with some pedogenic carbonate. Dunes may be up to seven metres high. Recent optically stimulated luminescence (OSL) dating at two sites (Sheard et al., 2006) indicated that dunes were deposited around 200 thousand years ago. These, perhaps unexpectedly old, ages for dune formation are consistent with the antiquity of the Great Victoria Desert indicated, e.g., Pell et al. (1999) who suggested that the sands of the central Musgrave Block–Officer Basin were derived dominantly from the Musgrave Block via fluvial transport in palaeovalleys with minimal net aeolian transport downwind towards the east. Nodular groundwater calcrete and gypsum-rich playa sediments are evident in palaeovalleys where sand dunes are absent (especially the Merramangye and Tallaringa palaeovalleys).

4.10.1. Musgrave Province and Officer Basin Palaeovalley Groundwater

Rainfall varies from 150–200 millimetres-per-year and mean annual pan evaporation rates are 3,000–3,600 millimetres in the Musgrave Ranges. Surface water and connected drainage systems are absent and the Great Victoria Desert dunefield is the dominant landform. Thus, groundwater is a valuable resource for indigenous communities, pastoral properties and mining operations. The regional groundwater potentiometric surface indicates flow towards discharge points in playas and at depth to the Eucla Basin, e.g., beneath the Eocene Ooldea Sand shoreline deposits (Lau et al., 1995). It is likely that deposits in some of the palaeovalleys are above the regional watertable and are unsaturated. Dodds et al. (1995) reported that the watertable at the southern end of the Lindsay Palaeovalley, west of Emu Junction, is 40 metres below ground level. They also reported that fresh potable palaeovalley groundwater is common in valley calcrete deposits at Maralinga, Oak Valley and Waldana Well. This association reflects enhanced local recharge due to runoff from hard calcrete surfaces. In the adjacent Western Australian part of the Officer Basin, Commander (quoted by Dodds et al., 1995) suggested that recharge to saline trunk palaeovalleys occurs from the interfluves and bores located on the interfluves are likely to intersect potable water supplies.

Bores in the Musgrave Province and Officer Basin occur in four main aquifer types (Miller, 1967; Tewksbury and Dodds, 1997; and Dodds, 1997):

- Weathered and fractured Precambrian bedrock in the Musgrave Ranges;
- Officer Basin sedimentary rocks in the southern part of the region;
- Cenozoic palaeovalley sediments; and
- Quaternary fluvial outwash at the margins of the Musgrave Ranges.

Earlier hydrogeological surveys did not recognise palaeovalleys and defined all Cenozoic sediments as Quaternary fluvial outwash deposits (Johnson, 1956; O'Driscoll, 1956). Miller (1967) recognised that there were connected basins associated with wider drainages which had relatively deep (>20–25 metres below surface) groundwater-bearing fluvial sediments and valley profiles not evident at the surface. Though not articulated as such, this is effectively the earliest known recognition of palaeovalleys in the Musgrave–Officer region. Most communities and outstations are located in the bedrock Musgrave Ranges and groundwater surveys have mainly concentrated there. Post-bedrock outwash sediments were preferred groundwater targets, due to easier site selection and drilling conditions, but as exploration progressed it was recognised that weathered and fractured bedrock, supplied by local recharge, held the lowest salinity groundwater supplies (<800 mg/L). To a lesser extent Quaternary surficial outwash aquifers also contain some fresher groundwater which is also used by indigenous communities and pastoralists. Palaeovalley aquifers are recognised as potentially having more abundant groundwater in most later hydrogeological surveys but are generally not water bore targets due to higher salinity (>1,500 mg/L). Thus the stratigraphic definition of palaeovalley sequences in the bedrock Musgrave Province remains poor. South of the Musgrave Ranges near Oak Valley, one of the few communities in the area, the Officer Basin sedimentary rocks extend from 30–100 metres below surface to Gawler Craton basement at 500 metres depth. Palaeovalleys are incised into the Officer Basin weathered palaeo-surface and widespread silcrete and Quaternary aeolian sands cover the area. Fractured/weathered bedrock and Quaternary fluvial outwash aquifers are not recognised here, and the Officer Basin sedimentary rock aquifers are unexplored and generally quite deep. Thus palaeovalleys are the most feasible groundwater targets (Tewksbury and Dodds, 1996; Dodds, 1997), although only limited drilling has been undertaken and relatively little stratigraphic information obtained.

Dodds and Clark (2003) investigated groundwater resources in the Fregon and Mimili areas of the Musgrave Ranges. Waterbores drilled in this region located fresh (~1,000 mg/L) water in alluvial sediments, although at greater than expected depths (typically 20–30 metres below surface). These groundwater resources probably occur in higher order tributary palaeovalley sediments, though there is scant mention of that possibility in Dodds and Clark (2003). At Fregon bores yielded 260–300 m^3-per-day of groundwater with TDS of 940–1,120 mg/L, whereas at Mimili bores have yielded 70–100 m^3-per-day of groundwater with TDS of 1,000–1,150 mg/L.

Stadter et al. (1979) reported results from a community water supply drilling program in 1978 when 16 of 24 bores drilled were successful, including four holes which were apparently sited in a palaeovalley aquifer (Table 4.14). In a major review of groundwater community supplies in the Musgrave–Officer region Tewksbury and Dodds (1997) evaluated wells based on 1:250,000 mapsheet areas and existing drilling logs (Table 4.15). For many bores, existing logs are insufficiently detailed to confidently identify palaeovalley aquifer sediments.

Table 4.14: Palaeovalley bore characteristics, Musgrave Ranges (from Stadter et al., 1979).

BORE STRATIGRAPHY	DEPTH (m)	YIELD (m^3/DAY)	SALINITY (mg/L)
Sands and gravels	40	194	2,322
Sands and gravels	40	38	540
Gravel underlying lake clay	60+	87	566
Calcrete	16	87	1,733

4.10.1.1. Groundwater Recharge

Groundwater recharge of weathered and fractured bedrock aquifers and Quaternary fluvial outwash deposits in the Musgrave Ranges occurs mainly due to infiltration of rainfall. This occurs either directly to the aquifer (i.e., in areas of outcrop) or via surface runoff in streams (Tewksbury and Dodds, 1997). Miller (1967) assumed that the recharge mechanisms are effective because of the generally low salinity (500–1,500 mg/L) of upper palaeovalley groundwater and rising salinity levels away from the upland ranges. However, direct study of recharge was limited to anecdotal observations of falling water-levels in drought and rising levels during wetter periods. Continuous recording of bore hydrographs commenced in the late-1990's (Dodds and Sampson, 2000, 2001; Costar and Sampson, 2004). Dodds and Sampson (2000, 2001) reported recharge due to high-magnitude rainfall events in early 2000 from community water-supply bores in the bedrock Musgrave Ranges. Most of these bores are probably sited in weathered or fractured bedrock aquifers which probably have direct lateral connection to palaeovalley aquifers (Table 4.16).

Table 4.15: Palaeovalley aquifer well evaluation Musgrave/Officer Basin region (data from Tewksbury and Dodds, 1997).

MAPSHEET NAME (1:250,000)	NUMBER OF BORES	BORE STRATIGRAPHY	WATERTABLE (m)	YIELD (m^3/DAY)	SALINITY (mg/L)
Mann	3	1-2 m silcrete/calcrete 3-7 m clay 35-40 m sand	10-12 m (top of sand)	35	
Mann	3	40-49 m clay, sand, sandy/gravely clay	24-40	320	800-1,700
Woodroffe	10	limestone, 70 m clay, sandy clay	16-24		2,300-3,100
Woodroffe-Lindsay	7	clays and sands		10-220	1,500-3,000
Lindsay	2	20-25 m sand, limestone, clay	3-4	85-170	1,500-3,000
Birksgate	4	10 m limestone	10	<45	4,000-30,000

Table 4.16: Musgrave Ranges community rainfall totals and extreme events for the period October 1999 to April 2000 (data from Dodds and Sampson, 2000).

COMMUNITY	RAINFALL FROM OCTOBER 1999 TO APRIL 2000 (mm)	LARGEST TWO-DAY RAINFALL EVENT (mm)
Indulkana	343	200
Amata	607	128
Kenmore Park	356	121
Pukatja	377	95
Fregon	281	73
Mimili	240	68
Pipalyatjara	407	30
Kalka	363	25

Bores at Indulkana, Amata and Pukatja showed significant water-level rise after the large-magnitude rainfall event which is indicative of major recharge. Rising water levels continued until late 2000 with bores at Amata rising 3–4 metres (Dodds and Sampson, 2001). Bores at other communities showed no recharge effects; this was probably because rainfall magnitude was insufficient, or because of suspected poor connectivity to the aquifer, especially in the case of Kenmore Park (Dodds and Sampson, 2000).

An attempt to quantify recharge was part of a review of regional water resources by Tewksbury and Dodds (1997) who used Thornthwaite’s Equation (Thornthwaite and Mather, 1957) applied to temperature and rainfall data from Ernabella. These calculations suggested that highly variable recharge occurred at 2–3 year intervals and averaged 48 millimetres-per-year (or 19% of rainfall) in the ranges, significantly decreasing southwards in areas of less rainfall. Tewksbury and Dodds (1997) stressed that the results could only be taken as a general guide because the method ignored other climatic factors such as wind strength, and various hydrogeological factors such as infiltration and connectivity. However, this estimate of recharge rate compares poorly with the much lower estimate of 0.05% of rainfall recharge derived by Allen and Davidson (1982), who used the ratio of chloride in rainfall and groundwater to derive their estimated value. Tewksbury and Dodds (1997) suggested that the use of chloride ratios in this manner may be questionable due to the remote nature of the location (far away from coastal areas). At best, both estimations are only indicative.

Dodds (1997) suggested that away from the ranges direct recharge to palaeovalley aquifers is minimal. Instead, groundwater is likely sourced from down-valley throughflow originating in the Musgrave Ranges, and via leakage from sub-artesian groundwater in underlying formations of the Officer Basin, e.g., the Murnaroo Sandstone and the fractured Observatory Hill Formation. The latter recharge mechanism is considered especially likely further south near the Ooldea Ranges where permeable Murnaroo Sandstone occurs at shallower levels.

4.10.1.2. Groundwater Quality

Potable groundwater occurs close to direct recharge sources in weathered and fractured bedrock aquifers and Quaternary outwash deposits in the Musgrave–Officer region. Palaeovalley aquifers obtain most of their groundwater from lateral leakage derived via surrounding bedrock and outwash aquifers. Groundwater salinity thus increases with distance away from the upland ranges. Fitzgerald et al. (2000) studied the chemical composition of groundwater from 129 bores in the Musgrave Ranges. Most bores occur in weathered or fractured bedrock but 26 bores tap Cenozoic sediments or calcrete deposits which include palaeovalley aquifers. Most of these bores contain groundwater which exceeds Australian Drinking Water Guidelines (ADWG) for boron, chlorine, fluoride, nitrate, sodium, total dissolved solids and total water hardness, although most groundwater is within ADWG limits for sulfate and uranium. Only one of the 26 bores has groundwater which is wholly within the ADWG.

With increasing distance away from the upland Musgrave Ranges, most bedrock and outwash aquifers are absent or inaccessible. Palaeovalley aquifers are thus the only accessible shallow groundwater resource across vast areas of the Musgrave–Officer region. At Oak Valley bores obtain groundwater from a palaeochannel sand aquifer situated near the indigenous community. This aquifer has a relatively high yield (~350 m^3-per-day) but the water is very saline (30,000 to 60,000 mg/L). Furthermore, groundwater is acidic ($pH < 4$), iron-rich and contains abundant radioactive elements – a toxic combination which renders the water unsuitable for use by the Oak Valley community. Low acidity and elevated iron levels are probably derived from oxidation of pyrite in the Pidinga Formation; thus most palaeovalley groundwater from the Pidinga Formation aquifer in this region will likely have similar characteristics (Dodds, 1997). However the source of high radioactivity is less certain. It may be due to a local source in the Lake Dey-Dey area (Tewksbury and Dodds, 1996) or it may be derived via throughflow from multiple upstream sources where high radioactivity levels are associated with granitoid bodies (Tewksbury and Dodds, 1997). If the source is local, radioactivity might not be as pervasive a problem in the Oak Valley area.

In addition to problems caused by acidity and radioactivity, groundwater in the Musgrave–Officer region commonly has fluoride and nitrate contents which exceed World Health Organisation (WHO) standards for potable water (Tewksbury and Dodds, 1997; Read, 1986). For example, Read (1986) investigated 45 bores in the area, with 25 of these containing groundwater with elevated fluoride and nitrate levels which exceeded WHO standards. Fluoride is derived from minerals such as fluorite, apatite and mica which occur commonly in crystalline basement rocks. The WHO upper limit for fluoride in potable water is 1.5 mg/L, although Read (1986) suggested that the US standard limit of 4 mg/L is probably more appropriate to use for the Musgrave–Officer region. At levels above about 10 mg/L crippling dental fluorosis can occur (Read (1986).

4.11. EASTERN EUCLA BASIN – GAWLER CRATON MARGIN

The Gawler Craton covers about 440,000 square kilometres of central South Australia and is an extensive region of Late Archaean to Mesoproterozoic crystalline basement rocks, essentially undeformed since 1,450 Ma (Fairclough, 2005). The major Archaean rock units consist of: orthogneiss and paragneiss which have been variably affected by granulite facies metamorphism, banded iron formations, chert, carbonate, calc-silicate rocks, quartzite, aluminous metasedimentary rocks, basalt, gabbro, pyroxenite and peridotite. Post-Archaean granitic intrusive bodies are also common. The Gawler Craton is substantially covered by thin Neoproterozoic to Cenozoic sedimentary rock units and regolith, including an extensive palaeodrainage network and associated Cenozoic palaeovalley infill sequences which are well developed along the eastern Eucla Basin margin (Figure 4.54).

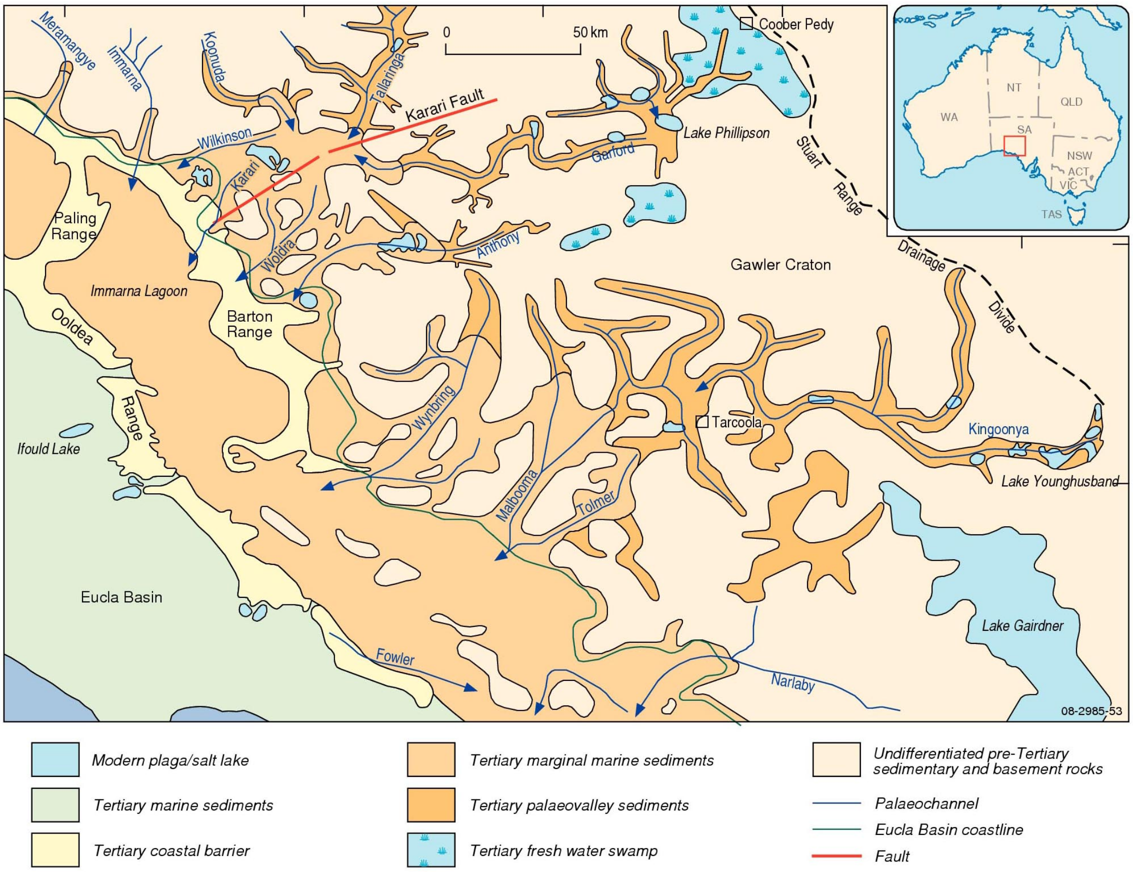


Figure 4.54: *Palaeogeographic reconstruction of the north-west Gawler Craton and eastern Eucla Basin during the Eocene, showing the distribution of fluvial, estuarine, lagoonal, coastal barrier and marine depositional environments. The intricate network of palaeovalley systems flow mostly south-west towards the Eucla Basin. Figure is modified from Hou et al. (2001) (Figure 3.24).*

The Gawler–Eucla palaeodrainage network is extensive and relatively well defined; individual palaeovalley systems include the Yaninee, Narlaby, Kingoonya–Malbooma–Tolmer, Wynbring, Anthony, Garford/Tallaringa–Woldra–Karari–Wilkinson–Koonuda, Immarna and Merramangye (Hou et al., 2003a, Drexel and Preiss, 1995; Hou et al., 2007). Compared with the Yilgarn Craton, the Gawler–Eucla palaeovalleys contain relatively few playas and the palaeovalley tracts are less apparent using standard mapping techniques. This is mainly due to widespread surficial cover and deep weathering of the infilling palaeovalley sediments. In recent years, extensive mineral exploration for placer, secondary uranium and mineral sand deposits near the Eucla Basin margin has focused considerable attention on the Gawler palaeovalleys and their infill sequences. Consequentially, the palaeovalleys have been the target of detailed studies by private companies and government agencies using remote sensing, geophysics and drilling (Hou et al., 2001). Thus, the distribution and stratigraphic architecture of many Gawler palaeovalleys are relatively well understood (Figure 4.55).

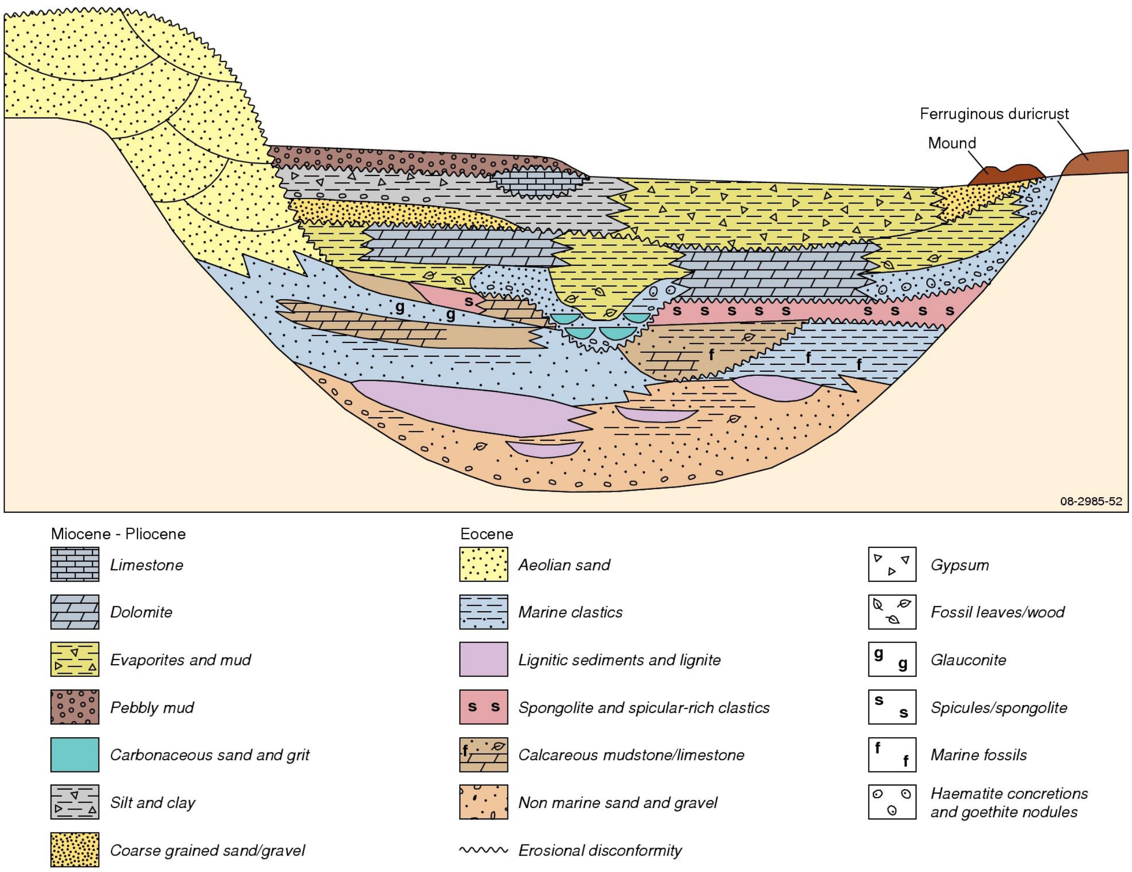


Figure 4.55: *Idealised Gawler Craton palaeovalley cross-section showing the complex stratigraphic relationship which may occur between various fluvial, estuarine and marine sediment deposits of Cenozoic age.*

The eastern Eucla Basin margin was not significantly affected by epeirogenic uplift in the Cenozoic (as occurred along the western margin). Consequently, the lower and middle reaches of many Gawler palaeovalleys have been subjected to considerable marine influence during multiple eustatic marine transgressions throughout the Eocene and the Miocene. These palaeovalleys were originally incised into pre-Cenozoic deeply weathered basement rocks, and were later infilled by variable fluvial, lacustrine, estuarine and marine sediments during several Cenozoic depositional phases, namely in: the Palaeocene to Early Eocene, Middle to Late Eocene, Oligocene to Early Miocene and Middle Miocene to Pliocene. Finally, the region has been blanketed by Quaternary surficial cover (Hou et al., 2003a). The dimensions of the Gawler palaeovalleys vary greatly, ranging from <100 metres to more than 30 kilometres wide. Valley depths may be up to 100 metres below the present land surface (Hou et al., 2003a). The lower palaeovalley reaches are characterised by estuarine facies deposits which interacted with Cenozoic lagoons and sand barriers, e.g., as now preserved in the extensive sand deposits of the Ooldea, Barton and Paling Ranges.

4.11.1 Cenozoic Evolution of Gawler–Eucla Palaeovalleys

During the Palaeocene and Early Eocene the Gawler Craton was cool and wet. This was probably a period of deep weathering and duricrust formation, and palaeovalleys were incised down from the recently uplifted Stuart Range drainage divide (situated to the north-east). Significant sedimentation events in the palaeovalleys began in the Middle Eocene with deposition of poorly sorted gravel-rich sand, carbonaceous sand, silty clay and sand- and clay-rich lignite horizons. These were deposited unconformably atop the older basement rocks. The oldest palaeovalley deposits in the Gawler Craton include the Hampton Sandstone and Lower Pidinga Formation (Hou et al., 2003a) and the Maralinga Formation (Clarke et al., 2003). Deposition of these sediments was initiated by the Wilson Bluff marine transgression. Massive to laminated carbonaceous gravely sands with carbonised wood and leaf fragments are dominant, and carbonaceous clay and lignite layers are also common. Marine-influenced lignite facies (estuarine) generally grade laterally to non-marine lignite facies (aggrading fluvial plains/swamps). During the higher eustatic sea-level of the Tortachilla transgression, the Lower Ooldea Sand was deposited as a barrier island complex (Ooldea Range), and marine influence extended several hundreds of kilometres up the palaeovalleys. Sediments were deposited in a variety of environments including fluvial channels, floodplains, estuaries and marginal marine systems. Relatively high rainfall produced abundant clastic material that dominated the marine sediments and diluted biogenic input (Alley et al., 1999). The Ooldea Range has considerably influenced palaeovalley drainage patterns since its construction, e.g., some diversions and constrictions through gaps were kept open as valley channels during sea-level low-stands, and formed tidal channels during high-stand periods.

In the Late Eocene warm and wet conditions prevailed and subtropical to warm-temperate rainforests were widespread throughout the Gawler. The Tuketja and Tuit marine transgressions reached higher levels and further inland than previous inundation phases, e.g., these reached topographic levels about 20 metres higher than the Tortachilla transgression. Similar to sedimentation patterns associated with the Tortachilla event, fluvial carbonaceous sand and lignite deposits in the upper palaeovalley sections grade laterally to marine and estuarine sediments. The Upper Pidinga Formation in palaeovalley channel and estuarine facies grades laterally and vertically to sponge-spicule bearing, very fine-to medium-grained sands of the Khasta Formation, which have clear evidence of a tidal setting (Hou et al., 2003; Clarke et al., 2003). These units include massive and finely laminated sediments, with cross-bedding or cross-laminated lenses present locally. The Ooldea Range existed as offshore sand islands and a new coastal barrier, the Barton Range, was constructed inland of the Ooldea Range in the Wilkinson and Anthony palaeovalley estuaries; this further complicated the local palaeodrainage network. The Kingoonya Palaeovalley system, situated further south-east along the Late Eocene coastline, has truncated the Barton Range barrier.

The latest Eocene to Early Oligocene was marked by marine regression and this is represented in the depositional record by an erosional break at the top of the Late Eocene horizons. In contrast, the Eucla Basin preserves little sedimentation history from the Early Oligocene Aldinga transgression. Only minor deposition occurred in the Oligocene; this is interpreted as a arid period with extensive erosion, weathering, silicification and ferruginisation of the upper Pidinga and Khasta Formations (Hou et al., 2003a). Sedimentation recommenced about the Mid Miocene when marine transgressions again raised sea-level to the seaward side of the Ooldea Range. Relatively more arid conditions reduced outflow and clastic sediment transport in the palaeovalleys resulting in the formation of nearshore limestone deposits and reworking of Ooldea Sand into an effective barrier shoreline. Consequently, this period was marked by non-marine deposition of the Garford Formation in the Tallaringa and Garford palaeovalleys, although limited marine influence likely extended to the Kingoonya (and other) palaeovalleys further south-east near the Ooldea Range (Hou et al., 2003a).

The Garford Formation predominantly comprises fluvio-lacustrine basal clayey sand (and minor sandy clay) which grades upwards through illite- and palygorskite-bearing clay layers to dolomitic clay and dolomite. The restricted fluvial influence in the Garford and Tallaringa palaeovalleys, represented by the extensive alkaline lake deposits of the Garford Formation, probably reflects reduced flow in relatively more arid conditions and restriction of the valley outflow by the reworked Ooldea Sand shoreline. The exact age of the Garford Formation is poorly constrained by palynology (Hou et al., 2003a) but the alkaline lake facies probably correlates to similar facies in the Etadunna and Namba Formations of the adjacent Lake Eyre Basin (Section 4.2). Overlying the Garford Formation in the Narlaby Palaeovalley are fluvial fine- to medium-grained, moderately to well sorted sands of the Narlaby Formation. This formation is partly silicified and iron-stained, and it may have been influenced by estuarine processes (Drexel and Preiss, 1995).

In the Late Miocene to Pliocene, uplift of the Eucla Basin platform led to subaerial exposure and karstic weathering of the Nullarbor limestone deposits. Consequently, minimal deposition occurred in the Gawler–Eucla palaeovalley systems because of reduced fluvial activity and increasingly arid conditions. Minor dolomitic carbonate deposits (with gypsum) and clastic sediments were formed with limited marine influence in the Kingoonya Palaeovalley during transgression (Hou et al., 2003a). In the Late Pliocene to Quaternary, extensive surficial deposits of relatively thin colluvial, alluvial, playa and aeolian dune and lunette facies have covered much of the landscape (Alley et al., 2003).

4.11.2 Major Palaeovalley Systems of the Gawler–Eucla Region

The Yaninee and Narlaby palaeovalleys are at the south-east margin of the Eucla Basin and trend westerly in relatively short, straight courses with minimal tributary networks. Formed well-away from the shoreline barrier of the Ooldea Range and the influence of uplift at the central and western Eucla Basin margin, the Yaninee and Narlaby palaeovalleys have probably been affected by marine or estuarine conditions associated with most of the eustatic transgressions which have occurred from the Eocene to the Pliocene. The Narlaby Palaeovalley has been extensively explored for secondary uranium deposits and mineralisation is associated with redox fronts developed near the contact between the carbonaceous, variably oxidised Pidinga Formation and overlying oxidised sand of the Garford and Narlaby Formations (Drexel and Preiss, 1995).

The Kingoonya Palaeovalley is one of the larger and more complex palaeovalleys draining the Gawler Craton. It has a large tributary network that trends westerly from the Stuart Range drainage divide north of Lake Gairdner to near Tarcoola where it turns south-west and develops into a complex mouth near the eastern extremities of the Barton and Ooldea barriers. There are a number of distributary palaeovalleys in the lower reaches, including the Wynbring, Malbooma and Tolmer systems. Chains of playas are relatively abundant in the upper reaches. The Cenozoic infill sequence consists of Pidinga Formation sediments overlain by the Kingoonya Member of the Garford Formation which is characterised by marine and estuarine influence (Hou et al., 2003a). The Kingoonya Palaeovalley infill sequence has been studied in detail by Hou (2004) from 16 drilling transects and multiple geophysical data sets.

The Anthony Palaeovalley trends towards the west and south-west and is relatively short with minimal tributaries. Compared with most other Gawler–Eucla palaeovalleys the Anthony system is poorly understood due to the lack of drillhole data. Thin, poorly sorted, silicified gravely sand horizons occur in the upper reaches and probably reflect relatively higher altitude (uplifted ranges) of the source area (Hou et al., 2003a). Alkaline lake deposits of the Garford Formation have not been recognised in the Anthony Palaeovalley (Hou et al., 2003a), suggesting that local variation in the nature of the sediment sequences occurs between some of the larger Gawler palaeovalleys.

The Garford Palaeovalley is relatively large and has an extensive tributary network that initially trends west-south-west, but becomes more south-west directed on the downstream side of its junction with the Tallaringa Palaeovalley. A complex valley mouth, characterised by multiple distributary channels (including the Woldra, Rarari and Wilkinson tributaries), interacts in the estuarine zone with the mouth of the Immarna Palaeovalley to the north and the Anthony Palaeovalley to the south. The estuarine complex is locally enhanced by the presence of the Karari Fault. The stratigraphic architecture of the Garford Palaeovalley is well constrained by eleven drilling transects (Figure 4.56) and multiple geophysical cross-sections (Hou et al., 2003a, 2003b). The alkaline lake Garford Formation fills an erosional depression in the underling Eocene Pidinga Formation carbonaceous sands. Bedrock rises from approximately 80 metres AHD in the lower reaches of the palaeovalley to 120 metres AHD in the middle reaches, representing a gradient of approximately 0.1%. Depth to basement is uncertain in the upper reaches. Negative gradients in parts of the lower reach imply post-Eocene tectonic disruption and suggest that detailed drilling control and tectonic reconstructions are both essential to accurately determine the valley morphology and sedimentary architecture (Hou et al., 2003a).

The Tallaringa Palaeovalley occurs at the northern Gawler Craton margin and trends south-south-west from the Stuart Range divide to link with the Garford Palaeochannel near its mouth. It has an extensive tributary network including branches which trend south-easterly from the upland Musgrave Province. The location and distribution of the Tallaringa Palaeovalley is well defined by remote sensing and geophysical exploration but the sedimentary infill sequence is poorly constrained as little drilling has been undertaken (Hou et al., 2003a, 2003b). However, the Garford Formation is known to unconformably overlie Pidinga Formation rocks, similar to the Garford Palaeovalley.

Increased exploration activity in South Australia for uranium and heavy mineral sand deposits associated with palaeodrainage systems and palaeocoastal sediments has driven demand for compilation of a state-wide thematic map. Recently, a preliminary edition of a 1:2 million scale map entitled ‘Palaeodrainage and Tertiary Coastal Barriers of South Australia’ has been produced by the South Australian Department of Primary Industries and Resources (Keeling and Hou, 2007; Hou et al., 2007). This mapping exercise has used a variety of datasets including the SRTM DEM (Shuttle Radar Topography Mission digital elevation model); Landsat 7 imagery, NOAA night-time thermal imagery, and drillhole data (refer to Chapter 5 for further details on use of these techniques for palaeovalley investigations). The map also includes a revised stratigraphic correlation chart of Tertiary sediments in South Australia.

Compilation of this thematic South Australian map has shown that the surface expression of palaeochannels as either topographic lows or inverted ‘silicified’ highs is confined largely to parts of the western and central Gawler Craton, Musgrave Province and Adelaidean Fold Belt. Elsewhere in South Australia the surface expression is generally very poor and palaeodrainage systems are largely obscured by a variable thickness of Quaternary sediment cover or regolith. In some places, these cover sequences may be several tens of meters thick. In such areas, the interpreted palaeodrainage distribution is based on an integrated dataset which includes information provided by drilling, remote sensing methods (particularly night-time thermal imagery) and geophysical surveys (e.g., airborne and transient electromagnetics). These data are combined with knowledge of continental sedimentation and the sedimentary history of Mesozoic, Palaeogene and Neogene channel sediments in South Australia (Keeling and Hou (2007).

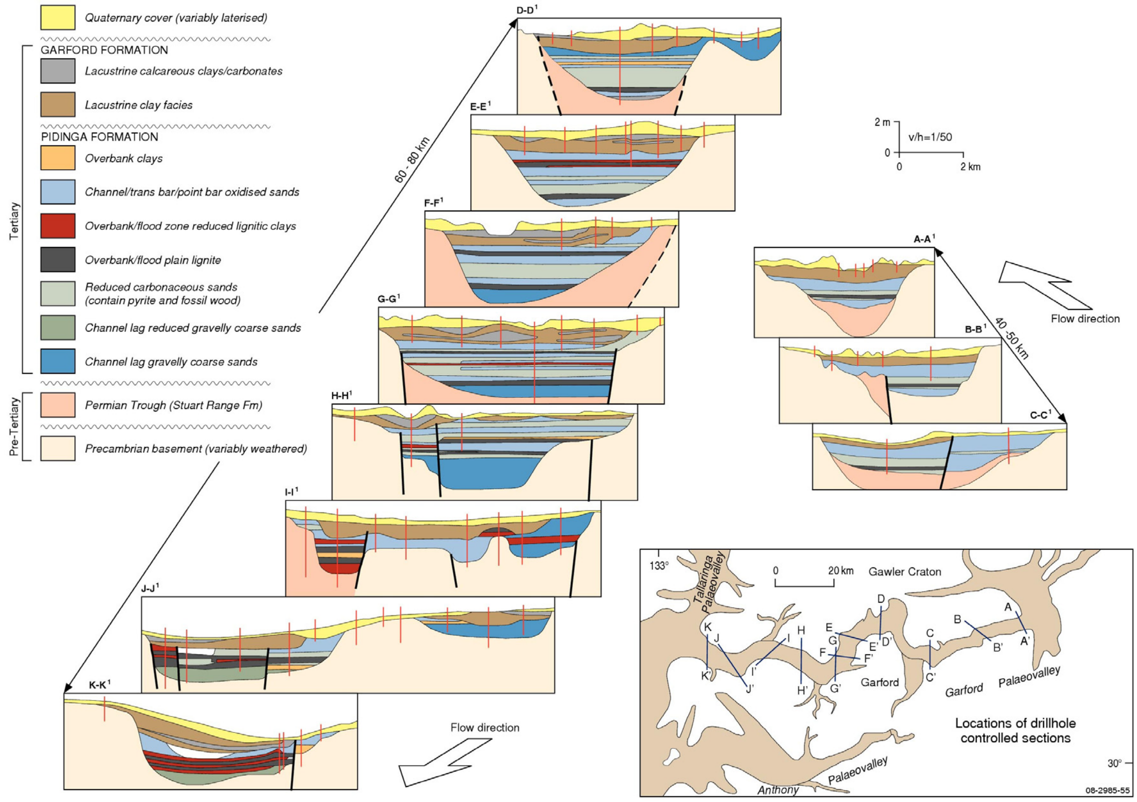


Figure 4.56: *Comparison of interpreted stratigraphic sections across the Garford Palaeovalley. The location of these eleven cross-sections, based upon detailed drilling transects, is shown in the inset map. Note the variable shape of the incised valley along-strike and the different sediment thicknesses. Figure is modified from Hou et al. (2004) (Figure 2).*

4.11.3. Eastern Eucla Basin – Gawler Craton Groundwater Resources

The groundwater resources of the Gawler Craton palaeovalleys are poorly documented, even for the Garford and Kingoonya palaeovalley systems which have been drilled along transects (Hou et al., 2003a, 2003b; Hou, 2004). The lack of knowledge about these groundwater resources is surprising given the absence of connected or perennial surface water resources across this vast region, which hosts multiple pastoral stations and an increasing number of mining operations, which typically require substantial water resources for personnel and ore processing.

Martin et al. (1998) suggested that groundwater resources in palaeochannel aquifers on the Gawler Craton are of crucial importance to the mining industry, as they have the potential to provide a significant water supply for ore processing and other mining operations. Drilling in the Garford Palaeochannel indicated a 10–15 metre thick palaeochannel sand aquifer which potentially contains up to 300 x 10^6 m^3 of saline groundwater in storage. From comparison to the Garford Palaeovalley, the larger Tallaringa Palaeochannel on the north-western margin of the Gawler Craton is estimated to contain a more extensive sand aquifer with up to 900 x 10^6 m^3 of saline groundwater. No individual resource estimates have yet been made for other Gawler Craton palaeovalleys but they are expected to contain similar quantities of groundwater. A first-order estimate of the total groundwater resources of the palaeodrainage network throughout the region indicated that up to ten times the combined total of the Garford and Tallaringa palaeovalleys may be available, i.e., ~12,000 x 10^6 m^3 of groundwater (Martin et al., 1998). Water quality generally ranges from about 5,000–70,000 mg/L but detailed information on bore yields and aquifer characteristics is not yet publicly available. Martin et al. (1998) indicated that anecdotal reports have suggested that some of the palaeovalley groundwater in the Gawler Craton may be artesian. It is clear that further more detailed studies into the nature of palaeovalley groundwater resources in the Gawler–Eucla region are required.

5. Exploring and Identifying Palaeovalleys and their Groundwater Resources

Palaeovalley identification and characterisation has progressively improved in both detail and scale as available data have increased and new investigative methodologies have developed. The initial observations by explorers and surveyors were broad-scale and backed by intuitive interpretations. However, the largely accurate early description of palaeodrainage networks by Carnegie (1898) indicates the high quality of his landscape observations. Various mapping techniques for soil, vegetation and geology tended to highlight the existence of palaeovalleys but the details of palaeodrainage networks including connections, interfluves, watersheds and drainage divides were only elucidated later when topographic elevation data became available. In more recent times improved topographic accuracy, via digital elevation models (DEM) and remotely sensed altimetry, has been combined with airborne and spaceborne remote sensing imagery and geophysical data (combined using geographic information systems or GIS) to accurately define palaeodrainages, including their detailed tributary networks. When combined with drilling transects the palaeovalley sedimentary architecture can also be elucidated.

5.1. VALLEY VERSUS CHANNEL

As explained in Section 1.3 channels and valleys differ in scale and characteristics, and this distinction should be maintained with reference to palaeoforms (Figure 1.2). This report restricts use of the term palaeochannel to discussion of ancient channel facies or forms within a palaeovalley sequence and the term palaeodrainage to refer to drainage networks of palaeovalleys. For exploration of palaeovalley resources it is also useful to discriminate between exploration techniques which can identify only palaeovalley location and dimensions and those which can determine the actual nature and location of the palaeochannel facies. This is particularly important with regard to groundwater resources as the palaeochannel facies are the major palaeovalley alluvial aquifers; these are narrower than the palaeovalley and have sinuous, unpredictable courses. There is typically no consistent or predictive relationship between palaeochannel facies and palaeovalley playas or salt lakes. Palaeovalley calcrete deposits, which can be extensive and important aquifers are generally near-surface, post-depositional features of the palaeovalley and are typically not related to the palaeochannel facies.

5.2. MAPPING

5.2.1. Soil and Valley-Form Mapping

Bettenay and Mulcahy (1972) reported on the identification of palaeodrainage networks in the south-west drainage division of Western Australia, based on soil and landscape data compiled at regional to larger scales for the Atlas of Australian Soils (Northcote et al., 1967). They demonstrated that repetitive patterns of valley form and associated soils and deep weathering were distinctive for three stages of river formation – which they termed old, mature and younger. The **old stage** referred to the palaeodrainage network east of the Meckering Line where the ancient landscape preserves deep weathering on the uplands (sandy with ferricrete, mottled and pallid zones on interfluves and drainage divides) and beneath surficial deposits on broad, low-gradient valley floors (saline and blocked by aeolian sediment). The landscape undulates and relief from upland to valley floor rarely exceeds 60 metres. The **mature stage** refers to valley modification due to incision initiated by rejuvenation, but with retained mature valley forms, which are U-shaped and have low gradients and are 30–75 metres below undulating uplands. Sandy ferricrete profiles with mottled and pallid deep-weathering horizons are preserved only on upland divides. Valley sides have extensive ferricrete-free slopes with fresher soils developed on exposed rock. Valley floors contain ferricrete deposits with pallid zones developed on water-laid deposits which become truncated and buried by alluvium downstream. The undulating uplands have similar gradients to those of the old drainage zone. The **younger stage** refers to deeply incised valleys of the lower rejuvenation zone, where the highly weathered, ferricrete-bearing uplands are of limited extent. Ferricrete-free valley sides with fresh rock outcrop are extensive. Valleys are V-shaped, deeply incised, and ungraded with rocky floors that lack valley deposits. Bettenay and Mulcahy (1972) also commented that bedrock lithological or structural control of drainage was rarely apparent for the old stage drainage but became increasingly evident in the mature stage and tends to dominate the younger stage. They also noted that suitability for agriculture increased from older to younger as the soils became less depleted and less saline.

5.2.2. Vegetation Mapping

Beard (1973; 1984) reported 1:1,000,000-scale natural vegetation mapping of the whole of the Western Australian state. The vegetation was classified into structural and floristic types which correlate with climate, landforms, soils and other physical features. This allowed Beard (1973) to identify and map palaeodrainage networks and individual palaeovalleys (Figure 2.1). In the course of vegetation mapping Beard (1973) noticed that the topographic pattern of the palaeodrainage network was evident in aerial photographs mainly due to the particular vegetation growing along them. In the drier desert areas, ferricrete plains are covered by 'Mulga Parkland' vegetation with mulga on the uplands and ferricrete breakaways. In the desert valleys, palaeochannels are marked by 'tree savannah' vegetation as well as incorporating lines of claypans and small lakes. Other desert area palaeovalleys are characterised by sand accumulations and have 'mixed shrub steppe' and 'desert oak' vegetation. The desert oak (*Allocasuarina sp*.) occurs as groves between the sand ridges in the topographic lows, apparently controlled by accessibility to the watertable. The desert oak often surrounds chains of salt lakes. In the wetter south-west drainage division Beard (1973) described similar differentiation between upland and valley vegetation types, which also discriminates palaeovalleys. The upland drainage divides and interfluves are characterised by 'mallee thicket' and 'heath' whereas 'woodland' occurs in the valleys. Beard routinely used aerial photography for the state-wide vegetation mapping and subsequently used the vegetation patterns to compile his initial state-wide palaeodrainage map (Beard, 1973) on 1:250,000 topographic base maps. However, the observations made by Beard are not necessarily applicable across the wider Australian arid zone; for example, desert oaks in central Australia have no particular association with palaeovalleys.

5.2.3. Topography

Valleys are, by definition, low points in the landscape and therefore topographic information is vital when mapping drainage patterns. In Australia, a continent marked by its long-term tectonic stability, the topographic imprint of drainage has survived for extremely long periods of time, up to 100's of millions of years in some places. Even where epeirogenic uplift or tilting alters the topographic expression at broad regional scales, the shape of pre-existing valleys can survive, superimposed in the new landscape because both erosion and deposition rates are extremely slow. These factors have combined to preserve many ancient palaeodrainage patterns and in most instances palaeovalleys are still actual valleys, though relief is subdued and drainage is not coherent. Survival of palaeoforms, or **topographic inheritance**, exerts strong controls over many physiological factors such as soil distribution, surface water and groundwater processes, landscape salinity and aeolian deposition; this, in turn, allows ready visual or cartographic recognition of palaeovalleys. However, the interfluves and watersheds between the palaeovalleys are more difficult to define and map, as they rarely form discrete or well-defined ranges. More often they form broad, low-relief, uniform sand plains or duricrust terrains, and accurate definition of palaeodrainage network boundaries is consequently difficult.

In remote areas of the Australian arid zone, topographic mapping has been restricted to scales of 1:250,000 or smaller, and originally these maps were not contoured. The first widespread elevation data was made available from gravity surveys undertaken by the Bureau of Mineral Resources and various oil companies. These produced an 11 kilometre-spaced grid of barometrically determined spot heights with an accuracy of ±7 metres. Contouring from even this relatively coarse data allowed improved delineation of many palaeodrainage networks, as shown by Bunting et al. (1974) and van der Graaff et al. (1977). Later editions of 1:250,000 topographic maps in the arid zone were contoured at 50 metres intervals, but still allowed Beard (1998; 1999; 2000; 2002; 2003) to further refine palaeodrainage patterns. However, in low relief areas, the contour interval of these topographic maps is too wide to unequivocally resolve some complexities of the palaeodrainage network, especially where drainage diversions or disruptions have occurred and where surficial cover is thick, as in the major dunefields. The much improved topographic resolution made possible by DEMs and airborne and spaceborne altimetry has allowed finer resolution of many different landscape elements, including palaeovalleys and palaeodrainage networks. For instance, Beard (1973; 2003) had been unable to resolve the relationship between the Throssel Palaeovalley and the Lake MacKay palaeodrainage using standard 1:250,000 topographic maps, and drew drainage divides between all of the Western Australian palaeodrainage networks and Lake MacKay, effectively defining the latter as a closed and internally draining basin. Sandiford et al. (2007) used modern altimetry data which demonstrated that significant post-Eocene uplift (at least 80 metres) had disrupted the upper Throssel Palaeovalley. They also showed separation between the Throssel Palaeovalley and Lake MacKay. Clearly the existence of a closed internally draining basin during the Eocene, a time of continent-wide and extremely positive hydrologic budgets, is counterintuitive and it seems likely that Lake MacKay had some connection to external drainage. However, such connection must have been disrupted by later tectonic activity and obscured by surficial sedimentation as it is no longer evident

5.2.4. Geological and Regolith Mapping

Until relatively recently, the focus of most geological research and mapping in Australia has concentrated on pre-Cenozoic terranes, almost certainly due to the focus on locating mineral or energy resources. Most areas of exposed bedrock have now been comprehensively explored for minerals; consequently there has been widespread recognition that improved exploration methods are required for areas with extensive surficial or regolith cover. At the same time, significant environmental issues and problems have arisen, such as dryland and basin salinity, which relate closely to the continent's long period of landscape quiescence. In this context Cenozoic geology and landscape studies have become increasingly important elements of geological mapping and research; especially through improvements in regolith mapping. Regolith collectively includes all weathering products, soils and sedimentary deposits that accumulate over time; deep weathering processes, duricrust formation, soil development and transported material all add to the regolith profile. This can have important consequences for mineral exploration as the processes of regolith formation strongly influence the mobilisation and redistribution of metal ions. A regolith map shows the distribution of various landform elements based on the dominant regolith processes. Three major landform regimes are generally recognised (Anand et al., 1998):

- **Residual regimes,** which have widespread preservation of relict land surfaces and associated regolith, i.e., ancient weathering profiles;
- **Depositional regimes,** whereby the accumulation of transported material exceeds erosion, and sedimentary sequences are consequently formed; and
- **Erosional regimes,** whereby the weathering profile is substantially removed or reworked.

Regolith mapping has played a major role in recognising and mapping palaeovalleys and palaeodrainage networks. Palaeovalleys have been increasingly identified as sites for placer deposits or supergene enrichment of primary mineralisation, sites for secondary mineralisation (e.g., some types of uranium deposits) and as significant groundwater aquifers (Figure 5.1).

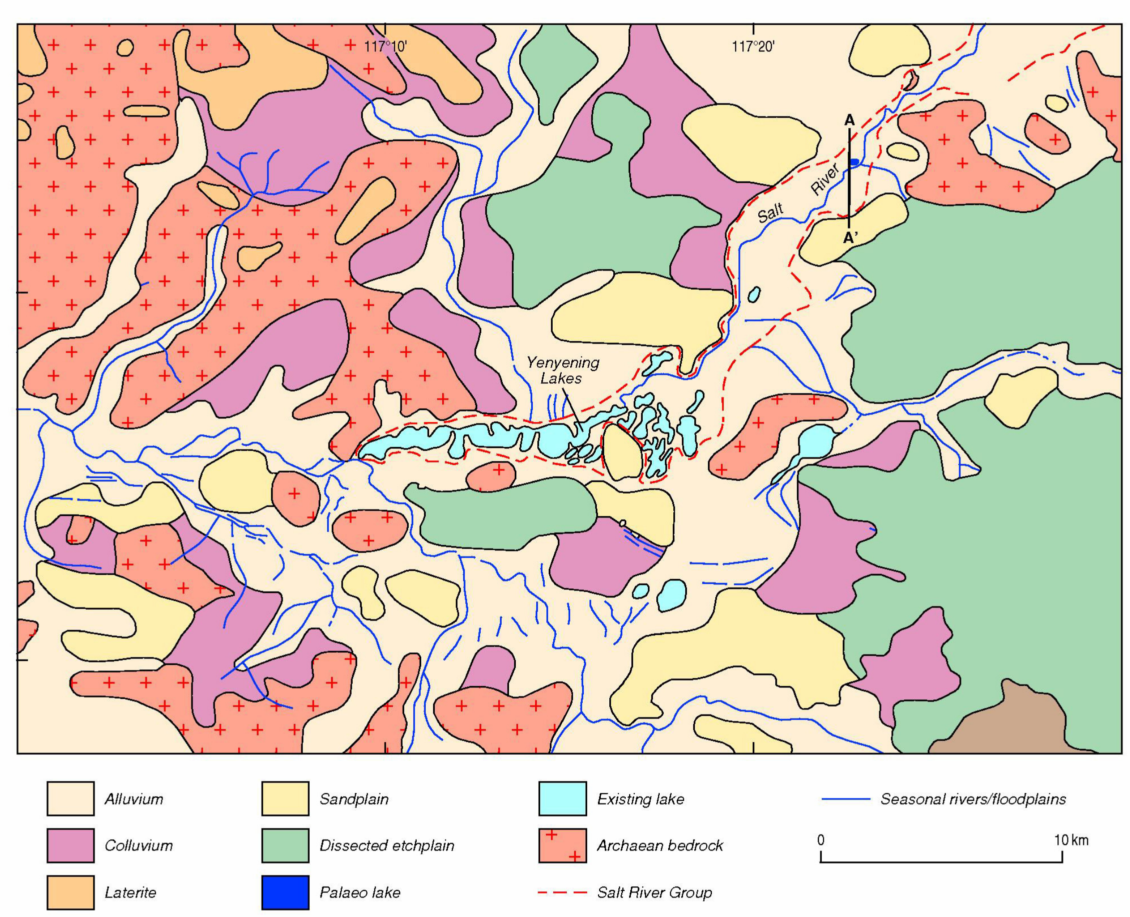


Figure 5.1: *Regolith map from around the Yenyenning Lakes in the Yilgarn region of Western Australia. Maps such as this can assist in mapping the distribution and orientation of palaeovalleys.*

5.2.5. Mapping Groundwater Resources

The mapping techniques discussed in Section 5.2 can delineate palaeodrainage networks and the spatial location and dimensions of individual palaeovalleys. However, these methods generally do not provide information on the subsurface stratigraphic architecture, or the nature and characteristics of the sedimentary material and groundwater resources of palaeovalleys. An exception is that mapping the location and size of playas within palaeovalleys can help delineate the location of major groundwater discharge areas.

5.3. REMOTE SENSING

Palaeovalleys are former river valleys now infilled with alluvial valley-fill and commonly covered by surficial sediments; they typically have little or no surface expression. Even playas, which are common surface landforms in palaeovalleys, do not necessarily conform to the former palaeochannel thalweg. Palaeovalleys can vary from tens of metres to kilometres in width and tens to hundreds of kilometres in length depending on the order of the stream in the palaeodrainage network. Palaeochannel sediments in the most deeply incised section of the palaeovalley, which are commonly the location of both groundwater and mineral resources, are randomly located in the palaeovalley due to stream channel migration processes. Thus, although higher-order palaeodrainage networks are commonly mapped using relatively straightforward techniques (Section 3.2), the detailed exploration of palaeovalley stratigraphic architecture and the delineation of lower-order tributary palaeodrainage systems require more sophisticated methods, combined with a solid understanding of the principles of modern fluvial sedimentology. As the subsurface varies enormously due to complexities of landscape evolution and local geology there can be a wide variety of responses to individual exploration techniques (Hou et al., 2001; Hou and Mauger, 2005). For this reason it is highly desirable for palaeovalley exploration to be based on the integration of multiple technologies, including visual and processed satellite images, digital elevation models, radar imaging and ground- or airborne-based geophysical surveys. Many of these techniques are remotely sensed on airborne and spaceborne platforms, and the information is derived in digital form which allows relatively easy combination in geographic information systems (GIS). Ultimately, drilling is required to demonstrate the veracity of remotely sensed data, particularly for groundwater resources to enable testing of water quality and quantity, and characterisation of aquifer parameters such as permeability and transmissivity.

5.3.1. Digital Elevation Models

Long-term tectonic stability has preserved palaeodrainage topography, though relief is subdued and drainage is not coherent. Topographic inheritance commonly allows recognition of palaeovalleys through the expression of secondary characteristics; however, direct topographic mapping is problematic due to relatively small differences in relief and the broad contour intervals of the largest scale mapping available in the arid zone. Digital elevation models (DEMs) provide ever-improving and higher quality relief information and clearly represent the best possibility for topographic definition of palaeovalleys in the arid zone (Figure 5.2).

Palaeovalley relief is minimised and obscured by valley infill, overlying surficial sediments and the development and migration of playas. Consequently, DEMs do not always permit the direct interpretation of palaeovalley boundaries, much less the palaeochannel facies (Hou, et al., 2000). However, palaeodrainage systems mostly coincide with topographic lows (Figure 5.2), although not all low-relief landscapes represent palaeodrainages (Hou and Mauger, 2005). High-resolution digital elevation models also have the potential to elucidate lower-order tributary palaeovalleys in the upper catchment reaches (Hou et al., 2000; Hou and Mauger, 2005). Another distinct advantage in using DEMs for topographic definition of palaeovalleys is their ready integration with other digital spatial data in GIS (Hou and Mauger, 2005).

5.3.2. Satellite Imagery

Many of the topographic and geological characteristics of palaeovalleys are indirectly expressed as secondary features associated with relief, vegetation, and soils, as well as the presence of playas, lunettes and sand dunes. Maps of these types of features were the original basis for the recognition and delineation of palaeodrainage patterns (Section 2.1 and 2.2.). Secondary features such as soils and vegetation are particularly evident in aerial photographs, and these were used in some of the earlier mapping exercises. However, the large size of the palaeovalleys, particularly in the down-valley direction, renders widespread use of aerial photographs prohibitively expensive and time-consuming. Air photo mosaics, which would address some problems of scale, are uncommon across much of the arid zone and, where available, tend to be spatially uncontrolled.

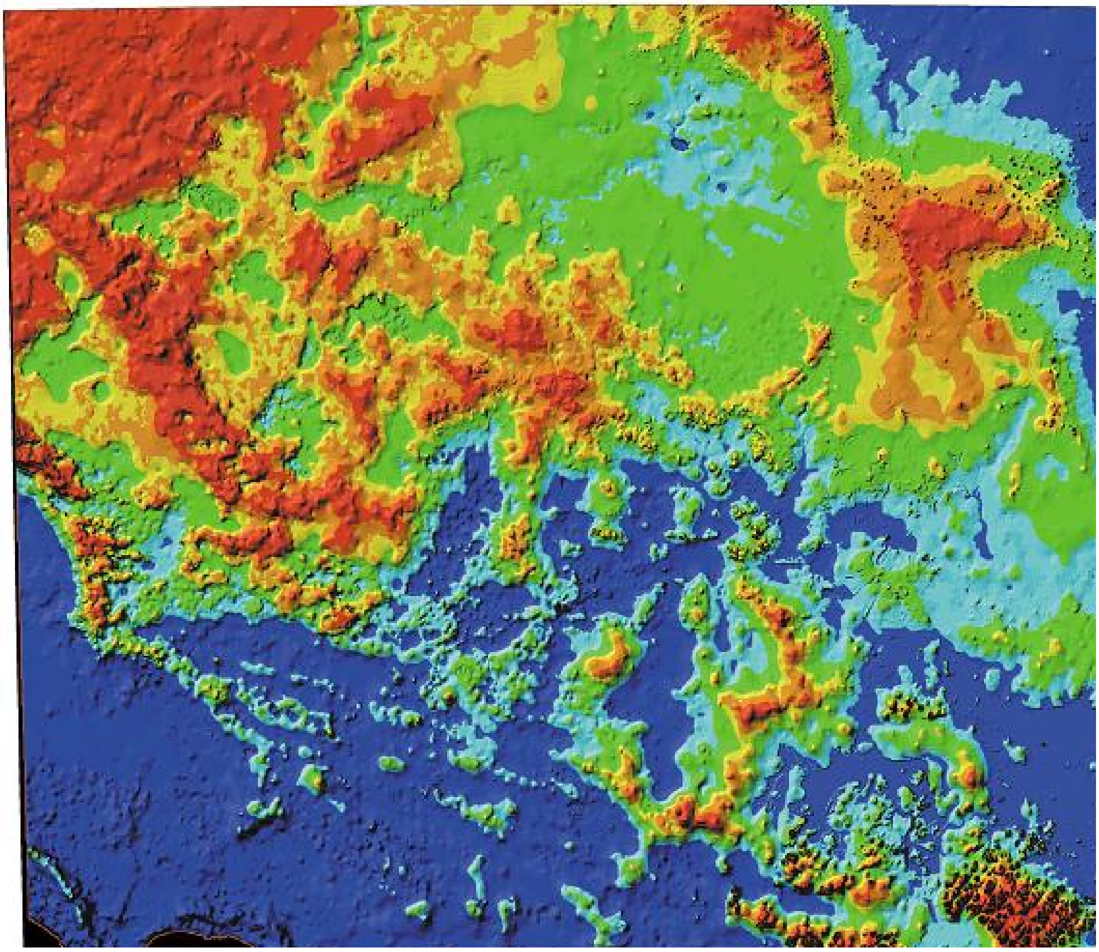


Figure 5.2: A six-level density plot from a digital elevation model of the north-west Gawler Craton, highlighting the modern relief pattern and the coincidence of palaeochannels with present-day topographic lows (after Hou et al., 2001). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.

Visual (unprocessed) satellite images, such as Landsat, SPOT or ASTER, are effectively analogous to small-scale aerial photographs or mosaics. On such imagery, palaeodrainage networks are frequently visible and mappable as dendritic networks, ranging from fine-scale tributaries to trunk palaeovalleys. The visual identification of palaeovalley systems using these images is due to the elevated albedo of characteristic palaeovalley landforms or minerals, such as carbonate, gypsiferous clay and playa surfaces (Hou and Mauger, 2005). The scale of satellite imagery is eminently suitable for mapping regional palaeodrainage networks. Satellite images have the additional advantage of being easy to spatially reference and import into GIS where they can be integrated or overlain with other digital data. Satellite images are also multi-spectral and can be processed using specialised techniques to enhance particular landscape elements; these can also be integrated with other digital data in GIS.

5.3.2.1. Landsat Thematic Mapper

Landsat Thematic Mapper (TM) measures seven bands of radiation in the visible and infrared (IR) range of the electromagnetic spectrum at a spatial resolution of 30 metres for all but Band 6 (120 m resolution). Landsat Multi Spectral Scanner (MSS) has been available since 1972 and Landsat TM since 1982; both have been widely used for geological and regolith mapping (Wilford and Creasey, 2002). The visible and near infrared radiance measured by Landsat integrates the soil, rock and vegetation characteristics and in particular can detect features related to the absorption of Fe oxides (Band 4) and clay minerals (Band 7). Landsat TM data requires geo-referencing and correction for atmospheric attenuation and backscatter, and can be processed as false colour or greyscale images, band ratios or Directed Principal Component Analyses of band ratios (Wilford and Creasey, 2002).

Processed Landsat TM imagery is useful for identifying spectrally anomalous and homogenous units, which can be equated to terrain units when draped over DEM data in GIS. Wilford (2000) used a three-band false-colour composite image highlighting clays (second principal component of ratio Band 4/3 and 5/7), iron oxides (ratio 5/4) and silica (Band 7 + 1). This image showed palaeovalleys, but with generally disappointing definition. Hou and Mauger (2005) also used processed imagery to identify palaeovalleys in the eastern Eucla Basin margin, using the ratios of Landsat TM bands to identify clay, iron oxide and silica (Figure 5.3). They found that the method was particularly useful in delineating the Tallaringa Palaeodrainage network where clay-rich palaeovalleys are incised into contrasting ferruginous duricrust terrain. Calcrete deposits of the Garford palaeovalley were also well-defined by Hou and Mauger (2005). However, correspondence with other palaeodrainage features was commonly problematic, even when Landsat imagery was combined with the regional DEM (Hou and Mauger, 2005). Landsat generally has a scale limitation for interpretation of around 1:50,000 unless the 15 metre resolution of the Landsat 7+ imagery can be used to enhance the spatial resolution of the other bands (Wilford and Creasey, 2002).

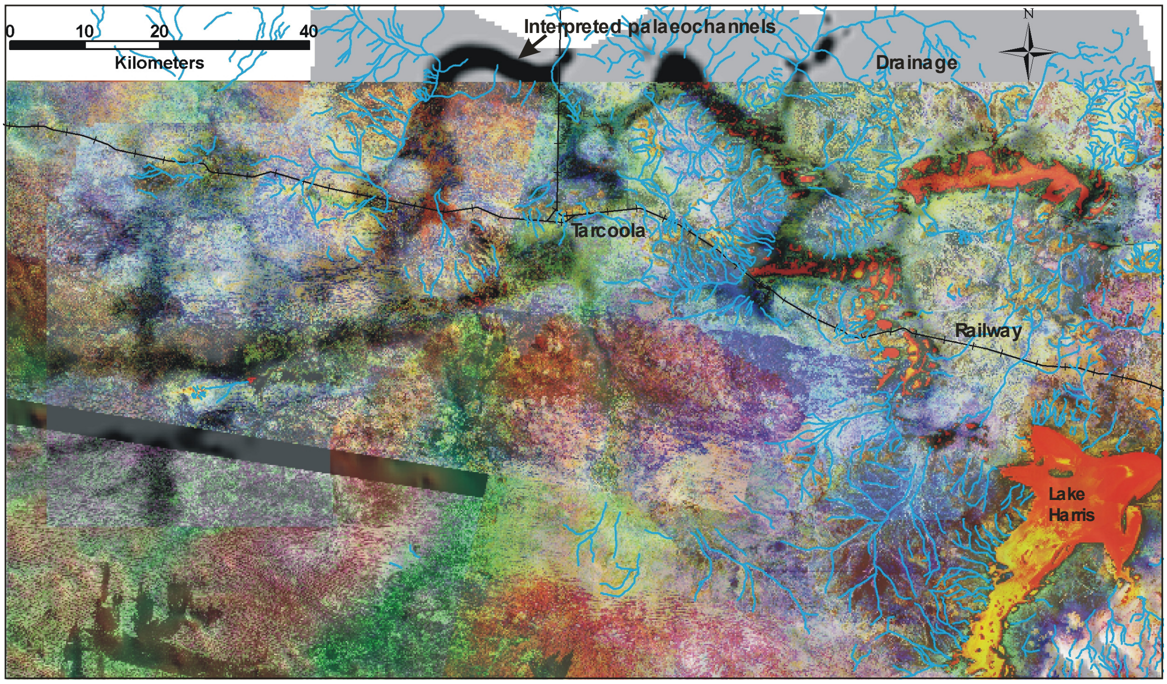


Figure 5.3: *Landsat TM image of the Harris Greenstone Belt in the Gawler Craton, superimposed on the regional digital elevation model. Palaeochannels are here interpreted from a number of integrated datasets, including satellite imagery and topographic data (after Hou 2004). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.*

5.3.2.2. ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite has 14 spectral bands including three in the visible spectrum (15 metre resolution), six in the short-wave infrared (30 metre resolution) and five in the thermal infrared (90 metre resolution). The ASTER system produces 60 x 60 kilometre scenes. The high number of bands allows processing to differentiate secondary regolith features related to palaeodrainage such as areas of clay, dolomite, calcrete, and gypsum (Hou and Mauger, 2005). ASTER better defines palaeodrainage systems than Landsat because of higher spatial resolution in the visible bands and because there are more thermal bands available for differentiating carbonate and silica (Figure 5.4). There is clearly a need to further test the capacity of the higher resolution of ASTER data and the larger number of spectral bands to identify palaeodrainage networks by enhanced processing.

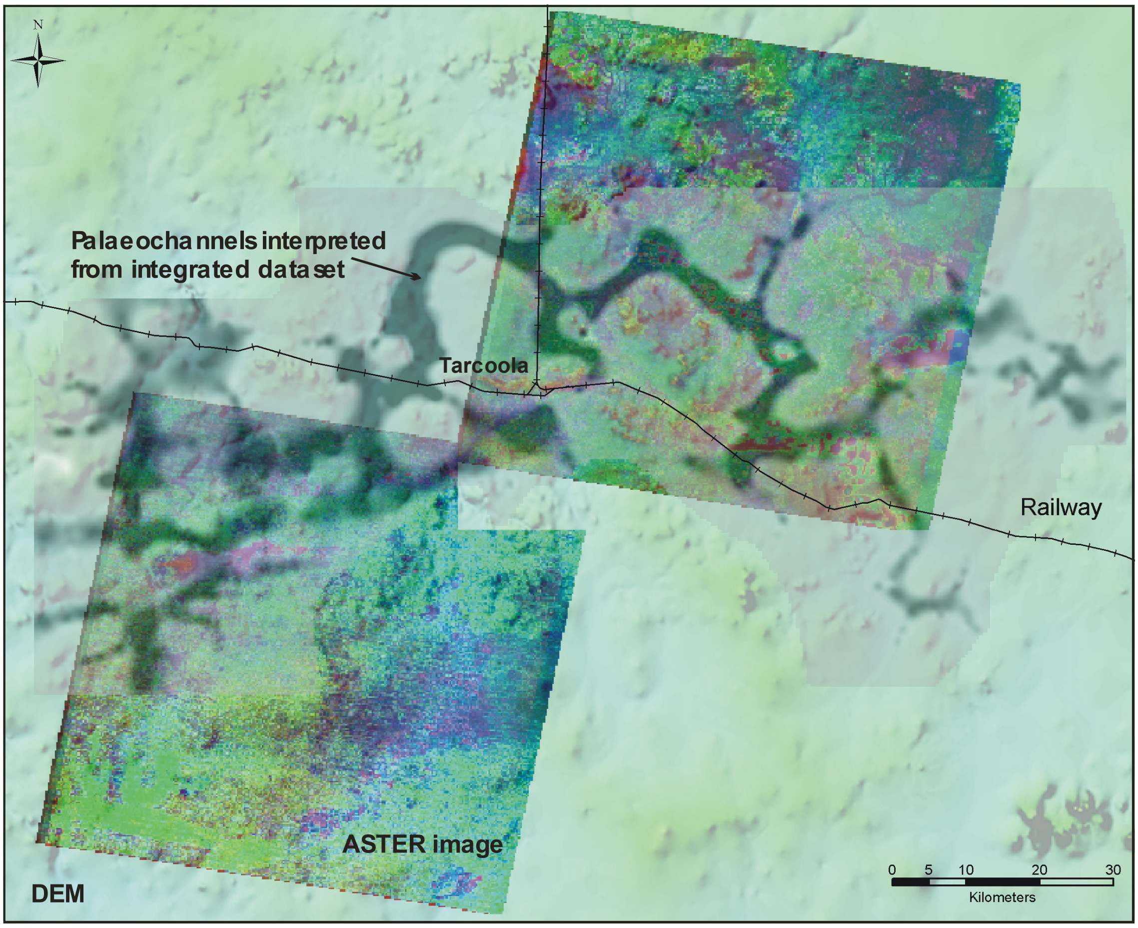


Figure 5.4: *ASTER images superimposed on DEM and palaeochannels interpreted from integrated data sets (after Hou, 2004). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.*

5.3.2.3. Night-Time Thermal Infrared

Thermal infrared satellite data records the radiant temperature that is a product of a material's kinetic temperature and emissivity, which is a measure of its ability to absorb and re-radiate thermal energy. Night-time thermal infrared (NTIR) data relates to mechanisms of night-time cooling and is influenced by the amount of thermal energy absorbed, the thermal properties of the material and the time of acquisition during the night. Thermal contrast effects take time to develop during the night depending on the nature of the contrasting materials and the ambient conditions such as degree of wetness and vegetation cover (Hou and Mauger, 2005). Several studies have shown that palaeovalley sediment infill is clearly evident in pre-dawn imagery, commonly with minimal processing applied to the data. This is due to the much larger temperature drop in the sediments compared to the surrounding basement rocks; this is largely because the clay-rich, moist channel fill material has much lower thermal inertia (Hou et al., 2000; Hou and Mauger, 2005; Stamoulis, 2006).

The National Oceanic and Atmospheric Administration–Advanced Very High Resolution Radiometer (NOAA–AVHRR) meteorological satellite has been most widely used for accessing thermal data (Honey, 1982, Hou and Mauger, 2005; Hou et al., 2000; Stamoulis, 2006). Tapley and Wilson (1985; 1986) and Tapley (1988) successfully delineated and mapped subsurface palaeodrainage networks and structural features in the Canning and Officer Basins using NOAA–AVHRR data. The NOAA–AVHRR detector and orbital configuration are suitable for interpreting palaeochannels because it highlights thermal variations due to moisture differences (Hou and Mauger, 2005). The major limitation of this system is the relatively coarse resolution of 1.1 kilometres, which degrades to 3.3 kilometres as the view angle increases off nadir. This largely restricts the use of NOAA–AVHRR to the delineation of large trunk systems and higher-order palaeovalleys (Hou and Mauger, 2005; Hou et al., 2000; Stamoulis, 2006). Moderate levels of processing are required to improve the clarity and detail of individual palaeovalleys. The time of acquisition is also critical (Hou and Mauger, 2005; Hou et al., 2000), although Hou (pers. comm. 2008) has suggested that the ideal time may vary regionally according to variations in climate, atmosphere and terrain.

The higher resolution of Landsat 5 and 7 TM data for NTIR analysis potentially offers enhanced definition compared to NOAA–AVHRR data. However, specific requirements such as use of optimal acquisition time and the need for cloud-free atmospheric conditions, combined with greater processing costs, generally precludes its use on a regional scale (Hou and Mauger, 2005). Additionally, Landsat TM offers only a single band of thermal data (Stamoulis, 2006).

The high resolution of ASTER and its multiple bands of thermal data suggest a high potential for NTIR analysis, even though the data are not continuously or automatically acquired as with NOAA-AVHRR and must be specially requested with resultant increased costs. Hou and Mauger (2005) analysed day-time images and found that the increased temperatures (compared to night-time) masked the more subtle thermal emissivity properties. They also found that empirical discrimination could be achieved through data processing by band ratios and decorrelation stretch. Stamoulis (2006) compared night-time NTIR data from both NOAA–AVHRR and ASTER for the same scene in the Northern Flinders Ranges of South Australia (including the Beverley Palaeovalley). The high resolution ASTER NTIR data provided structural, geomorphological and lithological data, including clear delineation of palaeovalleys, which was not at all apparent in the NOAA–AVHRR data. Unfortunately ASTER NTIR is not available in a wide range of night acquisition times, but the high spatial resolution available appears to outweigh the need to choose optimal conditions for acquisition, as suggested from NOAA – AVHRR data (Stamoulis, 2006). Clearly there is great potential in further investigating the use of ASTER NTIR data for delineating palaeovalleys.

5.3.3. Radar Systems

Subsurface palaeochannels have been the focus of integrated remote sensing studies in the eastern Sahara (Egypt, Sudan and Libya), the Negev Desert and northern Sinai of Israel, and the Al Labbah Plateau of Saudi Arabia, e.g., Berlin et al., 1986; Blumberg et al., 2004; Robinson et al., 2007.

These projects have successfully used remote sensing data to map the distribution of complex fluvial palaeodrainage networks which are now covered by extensive dune fields. In many cases, the palaeochannels are not evident on visible and near-infrared remote sensing images, e.g., aerial photography, Landsat TM etc. However, satellite- and shuttle-borne radar systems have the potential to elucidate these shallow subsurface features, due to the physical properties of radar waves and the local environmental conditions of the palaeovalleys (Grandjean et al., 2006).

Radar waves (which are part of the microwave portion of the electromagnetic spectrum) are uniquely able to penetrate unsaturated desert sands and provide an image of subsurface features (Robinson et al., 2007). Radar waves are not directly affected by sunlight (or other visible light sources) and are mainly influenced by the local surface inclination, roughness, and dielectric constant (of the ground). Signal penetration into the subsurface is possible if local ground conditions are favourable. Radar imaging is thus a valid and proven technique to remotely map spatially extensive geological or geomorphological features such as regional structural fabric or palaeodrainage networks. Imaging of buried features occurs because the microwave energy released by the 'active' radar system is conducted into the shallow subsurface without significant dispersion or attenuation of the signal. However, certain prerequisite environmental conditions are necessary to facilitate signal penetration below the upper few centimetres of the surface; namely that:

- The sand cover is fine-grained relative to the radar wavelength (the material must be at least one-fifth of the imaging wavelength, i.e., 'radar-smooth'); and
- The sand cover is physically homogenous and dry, with soil moisture content <5% (preferably <1%).

Successful radar imaging also requires a clear difference in the reflectance properties between buried palaeochannel deposits and the composition of the surrounding geological material.
Previous studies have shown that the depth of radar signal penetration will vary depending on wavelength (Robinson, 2002; Robinson et al., 2006). Radar signals consist of five data bands with varying wavelengths; these are termed P- (100 to 30 centimetres), L- (30 to 15 centimetres), S- (15 to 7.5 centimetres), C- (7.5 to 3.75 centimetres), and X-band (3.75 to 2.4 centimetres) (McVicar and Jupp, 1998). Longer wavelengths are capable of penetrating to greater subsurface depths; however, there is a corresponding loss of signal resolution which may lead to misinterpretation of imaged features. Most studies have employed C-band and L-band data (considered the optimal wavelengths for these investigations), with subsurface signal penetration estimated to vary from about 0.5 metre (C-band) to 2 metres (L-band), e.g., Robinson, 2002; Grandjean, 2006, Robinson et al., 2007. However, correlation of satellite radar data with actual field data (e.g., from auger holes or ground-penetrating radar) suggests that L-band waves may penetrate to depths of about 5 metres in optimal conditions, i.e., <1% soil moisture in fine-grained and homogenous sand (McCauley et al., 1982). The technique generally works best in hyperarid environments (very low rainfall areas such as the Sahara), but successful investigations have also been performed in arid to semiarid areas, such as the Negev Desert, e.g., Blumberg et al. (2004).

The spatial resolution of modern spaceborne radar systems is around 25 metres. At present, the best quality radar data for subsurface imaging is obtained from high resolution, multi-wavelength and multi-polarisation systems, such as the latest Spaceborne Imaging Radar (SIR-C) or Radarsat-1. The SIR-C system allows for different wavelength and polarisation combinations; these alter the level of contrast between the buried river channels and the surrounding blanket of sand, with some combinations more effective than others at producing coherent subsurface images. For example, the work in the Negev Desert showed that the most effective wavelength and polarisation combinations were: Band-L (HV polarisation); Band-L (HH polarisation), and Band-C (HH polarisation). In contrast to SIR-C, Radarsat-1 has only a single wavelength and polarisation signal (C-band HH), although it produces seamless images which cover more extensive geographic regions (useful for studies over spatially extensive areas).

The most successful palaeochannel-mapping studies have integrated radar remote sensing with visible and near-infrared (NIR) data and other geological (e.g., boreholes) and geophysical (e.g., ground-penetrating radar) datasets, e.g., Blumberg et al. (2004), Robinson et al. (2007). An accurate digital elevation model is also required to understand the variation of ground-slope within the survey region and to help constrain the surface drainage pattern. In areas of relatively thick sand cover (>5 metres thick), or where channels have dissected exposed bedrock, remote sensing data in the visible or near-infrared spectrum (e.g., derived from Landsat TM) are generally more effective (than radar) for imaging and interpreting drainage networks.

As indicated above, spaceborne radar systems can have great potential for detecting and mapping the distribution of buried palaeovalleys. This remote sensing technique could thus be an extremely useful research tool for elucidating palaeovalleys in Australia. However, radar imaging requires very specific environmental conditions to produce coherent images of the subsurface. Given the restricted criteria for successful radar imaging, it is uncertain if the Australian arid and semi-arid zones will be amenable to this technique; soil moisture levels are likely to be too high, sand cover may be too heterogeneous and coarse-grained and buried palaeovalleys may be covered by more than 5 metres of overburden. It is characteristic of much of the Australian dunefields that relatively widely spaced and well-vegetated dunes are separated by wide, finer-grained swales with even denser vegetation. It will be essential to have a thorough understanding of critical overburden parameters in each study area (e.g., the physical composition, moisture content, homogeneity, and thickness etc.), to judge if the acquisition and interpretation of radar data will be an effective analytical tool. However, given that the area of interest covers broad and remote geographic areas which lack other extensive datasets, there is little doubt that radar-based and other remote sensing data (visible and near-infrared) will be critical for palaeovalley delineation. Tapley and Craig (1995) and Tapley (2002) reported that AIRSAR (Airborne Synthetic Aperture Radar) polarimetric data successfully delimited sub-dunefield palaeovalleys in the Great Sandy Desert.

5.4. GEOPHYSICAL METHODS

Geophysical exploration methods have the potential to delineate the detailed palaeovalley stratigraphic architecture and groundwater resources of both higher- and lower-order tributary palaeodrainage systems. The primary aim of using geophysical methods is to define the form and nature of the palaeovalley to assist with siting boreholes in the deepest part of the palaeovalley. There are a wide variety of responses to individual geophysical techniques (Hou et al., 2001; Hou and Mauger, 2005) due to the variation and complexity of subsurface stratigraphic profiles and groundwater characteristics. For this reason it is highly desirable that geophysical exploration of palaeovalleys utilises ground-based and airborne methods, integrated with multiple remote sensing techniques. Most of these data are derived in digital form which allows relatively easy combination and analysis using GIS.

There are many different geophysical techniques used to investigate groundwater resources, including a wide range of proprietary instruments and software. Allen (2005a) has provided a comprehensive review of the equipment and instruments commonly available, with an assessment of their performance and suitability for various exploration objectives. Allen (2005a) suggested that the correct application of suitable geophysical techniques can:

- Detect and image shallow aquifers, such as palaeochannel sands;

- Image the degree of connection between aquifers and surface water bodies;
- Improve siting of boreholes by targeting the most prospective subsurface areas;
- Assist with groundwater modelling; and
- Be used for multi-depth imaging of soil properties and borehole logging.

Drilling is generally necessary to verify the physical characteristics of aquifers and their groundwater resources, and to enable testing of water quality and quantity etc.

5.4.1. Gravity Surveying

There is a significant density difference between Cenozoic palaeovalley infilling sediments (1.8–2.0 grams-per-cubic centimetre) and surrounding (commonly Precambrian) basement rocks (2.4–3.0 g/cm^3). Thus there is excellent potential for gravity surveys to detect the mass deficit resulting from replacement of the denser basement rocks by the palaeovalley infill, particularly where the palaeochannel thalweg marks the deepest section of channel infill and the steepest palaeovalley margins (Figure 5.5) (Hou et al., 2000). However, some geological conditions can complicate or compromise the interpretation of gravity data for palaeovalley delineation, such as variations in basement density, reduced density of deeply weathered basement (which minimises the contrast between basement and valley infill) and the presence of older sediments underlying palaeovalley infill (Hou et al., 2000). The spacing of survey lines or grid points and their orientation relative to the palaeochannel direction are also important considerations (Tracey and Direen, 2002). For example, gravity surveys designed for regional geological studies are unlikely to result in well-defined palaeovalleys. Gravity surveys conducted specifically for palaeovalley investigations are best conducted as detailed ground-based transects oriented perpendicular to the palaeovalley trend (Figure 5.6). They are also most effective when combined with other geophysical methods such as transient electromagnetic surveys (Hou et al., 2000; Tracey and Direen, 2002). Extremely accurate levelling data are required for each gravity station; the advent of differential GPS has simplified the process and rationalised the cost of obtaining suitably accurate data.

Smyth and Barrett (1994) used gravity investigations to define palaeovalleys in the Yilgarn Craton and concluded that gravity was most effective when integrated with electromagnetic survey and drilling data. Similarly, Johnson et al. (1999) investigated the Raeside and Carey Palaeovalleys of the north-eastern Yilgarn where deep palaeovalley fills are overlain by relatively thick continuous units within the broad and featureless palaeodrainage network. They used gravity (nine transects with a Scintrex CG-3 gravity meter) and transient electromagnetic (TEM) surveying, and a combination of both methods (one transect), at 100 metre station intervals across entire palaeovalleys to test the efficacy of these methods for identifying palaeovalley sequences. Gravity and TEM were found to be complementary, with both methods responding to contrasts in different physical properties of subsurface materials. Gravity was used where main channels were deeper and the density contrast between the unconsolidated channel sands and the denser bedrock produced anomalous and distinctly lower gravity readings, and also where TEM was affected by shallow-level, highly conductive hypersaline groundwater. Overall, the survey results provided excellent detail of the buried palaeovalleys (Tesla-10, 1997), particularly where both methods were combined.

Wilford (2000) reported the results of a gravity survey in the Granites/Tanami region, based on a mosaic of different ground-measurement densities with acquisition by a Scintrex CG3 digital gravity meter, located by differential GPS. Enhanced data from this survey were used for interpreting regolith, and palaeovalleys were clearly delineated in gravity images and cross-section transects, though Wilford (2000) indicated that the same palaeovalleys were more accurately identified by interpretation of aerial photographs and satellite imagery. Wilford (2000) also suggested that higher resolution gravity surveys would probably be successful in identifying higher-order palaeovalleys. Holzschuh (2002) tested a gravity survey in conjunction with reflection and refraction seismic surveys in a palaeovalley already well-defined by drilling. The drilling and seismic results were used to constrain processing of gravity data and the results accurately delineated the profile of the bedrock–palaeovalley boundary.

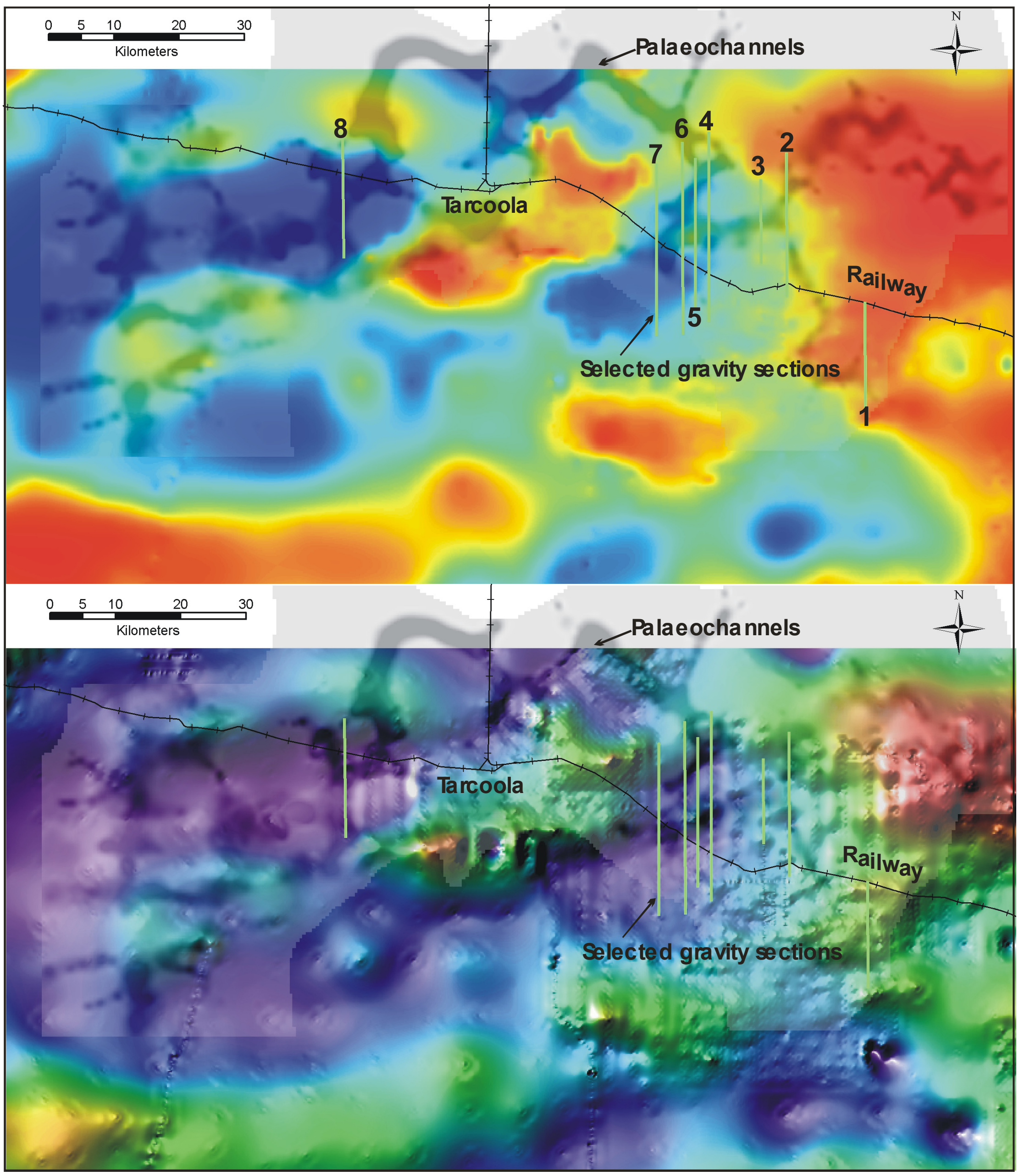


Figure 5.5: *Gravity survey image for part of the Harris Greenstone Belt in the central Gawler Craton. These data show that the regional Bouger gravity pattern is not influenced by the Kingoonya Palaeochannel. North-oriented traverse lines correspond with the eight gravity profiles shown in Figure 5.6 (after Hou, 2004). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.*

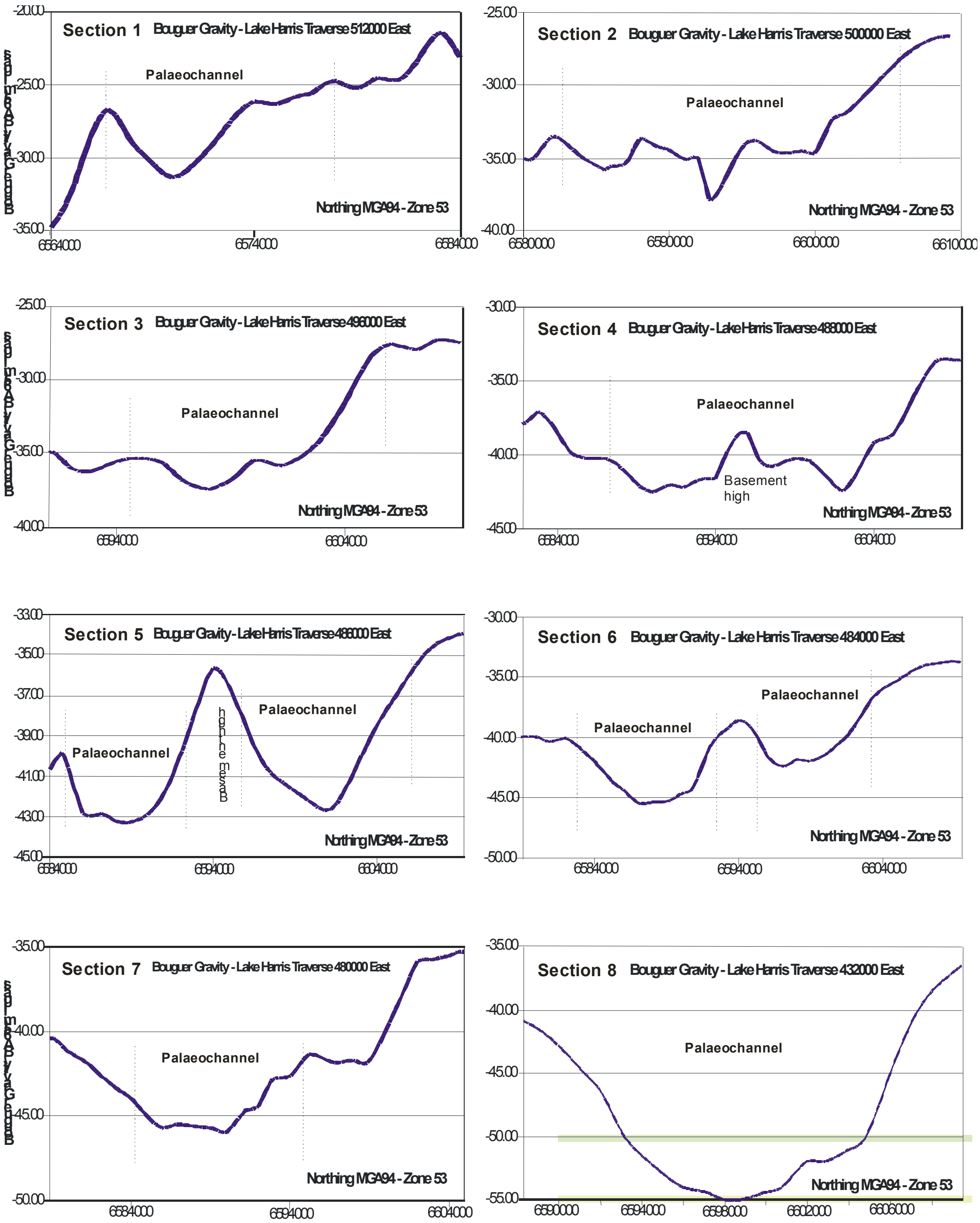


***Figure 5.6:** Ground-based gravity survey profiles across the Kingoonya Palaeochannel in the central Gawler Craton (section locations shown on Figure 5.5). These uncorrected gravity data clearly show that pronounced gravity lows are associated with the location of the palaeochannel (after Hou, 2004). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.*

P. Commander (pers. comm. 2008) indicated that gravity has been the most useful method to define the palaeovalley subsurface profile in parts of the Yilgarn Craton, especially where palaeovalleys are eroded into homogeneous bedrock such as granite. Finally, it is important to remember that, although gravity can be extremely useful in delineating geological structures which may control the presence or movement of groundwater (including within palaeovalleys), it cannot directly detect groundwater itself.

5.4.2. Electromagnetic Methods

Electromagnetic (EM) methods determine variations in electrical properties within the earth, particularly inductive electrical conductivity, which measures how easily electrical current can pass through geological materials (Lane, 2002). Conductivity depends on both solid materials (i.e., the rock mass) and groundwater, and is further affected by the porosity, arrangement of pores and degree of saturation in the subsurface. Unweathered rocks are generally a poor electrical conductor, unless graphite or metallic minerals with iron, copper or nickel are present; hence, variations in conductivity are generally governed by groundwater quantity and salinity (Lane, 2002).

There are several proprietary EM systems available (e.g., see discussions in Burval, 2006), but all typically involve active transmission of electromagnetic energy, interaction of this energy within the ground and reception of secondary-induced energy at a receiver. EM system end-members are frequency-domain (FD) and time-domain (TD) systems, although some EM proprietary systems may combine these two methods. FD systems transmit a magnetic field signal at a single frequency with sinusoidal amplitude variation and the recorded response is described by its total amplitude and phase compared to the transmitter signal, or by the amplitude of in-phase and 90º out-of-phase components compared to the transmitter signal (Lane, 2002). TD systems transmit a magnetic field signal with a sharp step and the time decay of currents induced in the subsurface is sampled at a number of delay times following the step change in transmission (Lane, 2002). Depth of penetration is a function of frequency or delay time such that shallow vertical resolution is determined by high frequency/early time performance and deep penetration by low frequency/late time (Lane, 2002). EM measurements can be made by ground-based or airborne (AEM) instruments, with the latter allowing systematic coverage of large regional areas (at the relative expense of detailed spatial resolution, near-surface vertical resolution and depth of penetration, Lane, 2002). Survey line spacing is important to define prior to the start of the investigation, and should be matched to the expected dimensions of the smallest features to be detected.

Hou et al. (2000) and Hou and Mauger (2005) indicated a strong conductivity contrast between palaeovalley infilling sediments and fresh basement rocks, but little contrast with deeply weathered basement or older sedimentary rocks. The propensity for palaeochannel sands to be saturated with more abundant and higher salinity groundwater enhances their delineation by EM and can allow definition of the channel base by TEM (Hou et al., 2000) or detailed lower-order tributary patterns by AEM (Hou and Mauger, 2005) (Figure 5.7). Hou et al. (2000) also reported that TEM could not differentiate between palaeovalley sediment fill and sediments of an underlying Permian Trough which presumably contained similar groundwater properties to the palaeovalley. Lane (2002) detailed results from an AEM survey in the vicinity of the Challenger gold deposit in the Gawler Craton, South Australia, where relief is subdued and a variable thickness of weathered and transported regolith obscures the subsurface features. The survey clearly delineated 200 m deep palaeovalleys near Challenger filled with conductive material interpreted as channel-fill sediments with saline groundwater. This was confirmed by drilling which encountered 210 m of alluvial sediment and lignite above weathered gneissic basement. The water resources of the basal palaeochannel sands were evaluated for use in mine processing at Challenger.

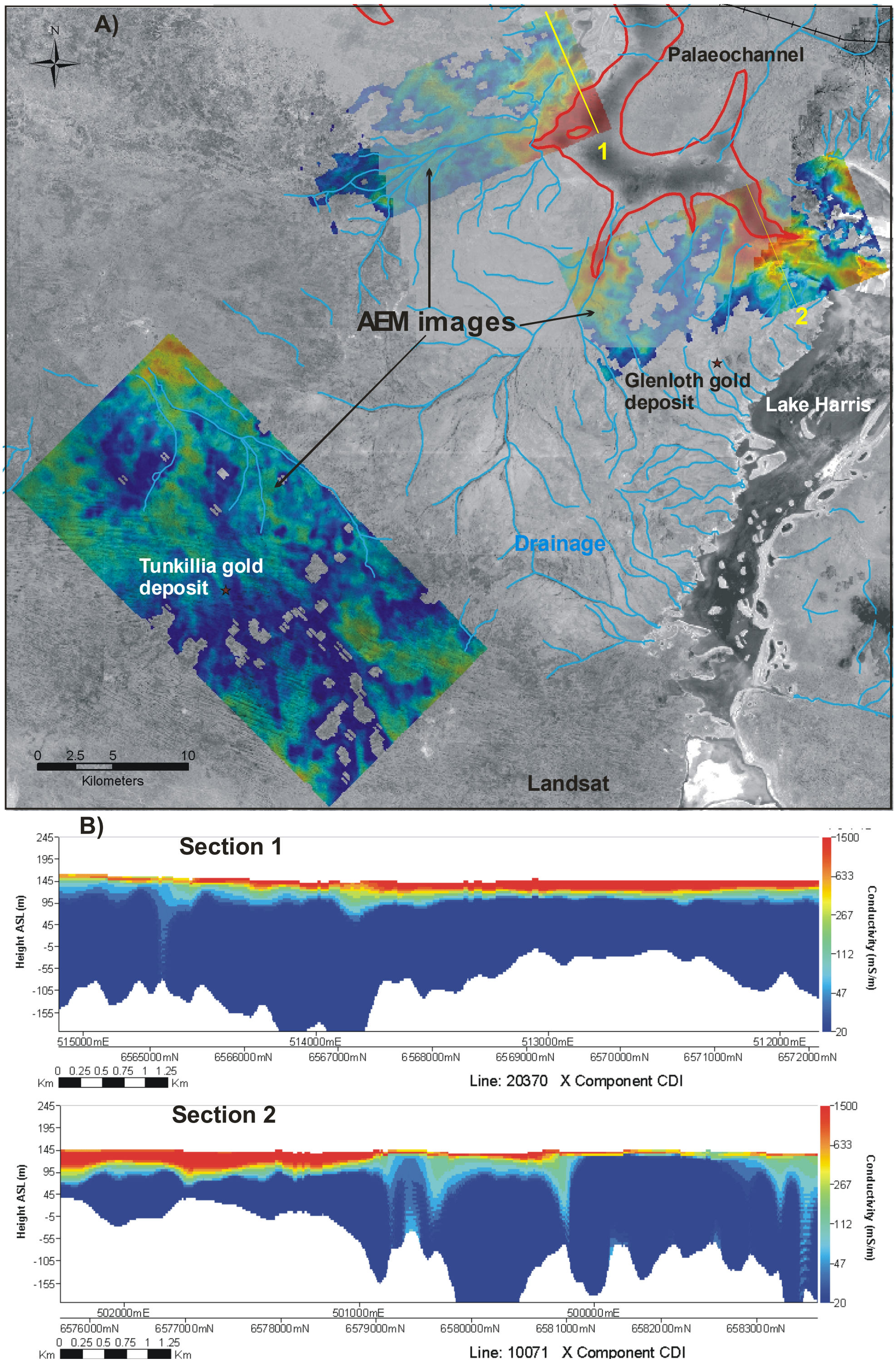


Figure 5.7: *Airborne electromagnetic survey data from the Harris Greenstone Belt in the central Gawler Craton (South Australia) showing: A) the correlation of high conductivity zones with the trend of the Kingoonya Palaeochannel, north-west of Lake Harris. B) Selected conductivity cross-sections through the Kingoonya Palaeochannel (section locations are shown in A) (after Hou and Mauger, 2005). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.*

5.4.3. Electrical Conductivity/Resistivity Methods for Groundwater

Groundwater, via the presence of dissolved salts, allows electric current to flow in the ground via ionic conductivity. Electrical conductivity (EC) is the most commonly measured property in groundwater investigations. The relationship of EC and its inverse, resistivity, to rock, soil and groundwater properties is well-defined (Geo-hydrology, 2007). Hard, fresh rock and dry porous sand lacking clay are highly resistive materials. The resistivity of porous or fractured rock or sediment, which contains free water, depends on the salinity of the water and the nature of the porosity. Impermeable clay with bound-water has low resistivity, and mineral (iron or metal sulphide) ore bodies have very low resistivity due to electronic conduction (Geo-hydrology, 2007). Low resistivity in a non-clay material is generally caused by either high porosity or low water resistivity, i.e., high salinity.

To measure ground resistivity, a current is transmitted with two electrodes and the potential created by the circulation of this current is measured by two other electrodes. The wider the spacing between the transmission and receiving electrode pairs the greater the depth of subsurface sounding. Lateral displacement of all four electrodes permits lateral profiles to be determined (Geo-hydrology, 2007). In hard rock, highly resistive terranes a low-resistivity anomaly may indicate groundwater, whereas in a clayey or saline environment a high-resistivity anomaly may indicate fresher water. Electrical methods can indicate the porosity but not the permeability of an aquifer (Geo-hydrology, 2007).

Allen (2005a) indicated that the capabilities of electrical detecting instruments are relatively well-known, and provided web internet addresses for modelling and simulation software to help select appropriate instruments. Instruments should be selected according to their ability to affordably map appropriate depth intervals. Multi-depth detection is commonly most appropriate so that the EM variation at different depths can be ascertained. Inversion processing can convert data from multi-depth devices into layered true EC data, without smearing data from different depths. This decreases reliance on actual samples from different soil and rock types at different depths. A single-depth device may cover a large depth interval; however problems can occur, e.g., when a deep but very high EC anomaly appears the same as a minor shallow-depth anomaly. Multi-depth EM devices can separate such responses, and are thus highly useful instruments.

All EC data, regardless of the source, can be combined into a common output format and a national on-line database has been proposed (Allen, 2005b). Depth of exploration, productivity and vertical and horizontal spacing are the principle considerations in choosing EC equipment and a system of correlation and calibration is required to convert EC data to the required properties. This can take the form of multi-depth salinity assessed soil samples or simply ad-hoc speculative analysis, which combines all available information.

Software for processing and presentation of EC data is as important as the instrument chosen to collect the data. Many packages are available with varying capacities to accelerate, automate and enhance the processing and resolution of EC image data. Different visualization solutions are also available and some software can provide real-time or near-real-time imaging solutions during data collection (Allen, 2005a). Further information on various software systems is provided by Allen (2005a).

5.4.3.1. Frequency Domain Electromagnetics (FDEM)

Frequency-domain EM (FDEM) systems image the subsurface EC using electromagnetic pulse rings of current that dissipate into the earth. Depth of penetration is varied by altering the:

- Coil separation and/or orientation;
- Frequency; and
- Height of the instrument above the ground.

FDEM instruments transmit a time-varying sinusoidal magnetic field and the sampling volume is dependant on geometry, with the frequency of the field consistent with a low-frequency-approximation. This assumption is commonly border-line in Australia's saline conductive soils and may need to be calibrated using soil samples from the survey area, or overcome by using rigorous inversion software. Thus calibration of FDEM instruments is critical for correct operation but can be difficult (Allen, 2005a). Further information on the suitability and performance of over twenty FDEM instruments is provided by Allen (2005a).

5.4.3.2. Time Domain (Transient) Electromagnetic (TEM)

TEM systems transmit a magnetic field signal with a sharp step and the time decay of currents induced in the subsurface is sampled at a number of delay times following the step change in transmission (Lane, 2002). TEM devices can efficiently image the deeper subsurface but have difficulty resolving the upper five metres. They require a large transmitter coil and an adjacent receiver coil. Traditional geological surveying systems use loops laid out by hand, but groundwater survey devices may use smaller loops on non-conductive vehicle-towed trailers. There is little difference in the performance of vehicle-towed and most airborne systems (Allen, 2005a). Further information on the suitability and performance of TEM instruments is provided by Allen (2005a).

5.4.3.3. Airborne Electromagnetics (AEM)

Allen (2005a) suggested that there is little difference in the performance of vehicle-towed and most airborne EM systems, except that the latter permit faster acquisition of data across much larger areas (but at considerably increased costs). The difficulty of removing the effect of aircraft altitude may hamper airborne devices from accurately imaging near-surface features, but they are an ideal method for defining and characterising larger regional aquifers or aquitards. Some AEM systems can be configured to image the thickness and conductivity of relatively shallow conductive surfaces or to image hundreds of metres into the ground, but they mostly cannot simultaneously resolve both shallow- and deep-seated geological features from the same survey. Further information on the suitability and performance of various AEM instruments are provided by Allen (2005a).

5.4.3.4. Geo-Electrics

Geo-electric devices use simple electrical fields rather than more complicated electromagnetic methods. In some groundwater surveys this can be an advantage over EM systems, resulting in less ambiguous data. However, these devices require very good electrical connection with the ground for optimal operation, and this is normally only achieved by hammering electrodes into the ground, by capacitive coupling, by weight, by ploughing devices or by innovative electronics (Allen, 2005a). Geo-electric systems are either terrestrial (person-carried or dragged), vehicle-borne or water borne. Further information on the suitability and performance of geo-electric instruments is provided by Allen (2005a).

5.4.3.5. Magnetotellurics (MT)

The MT method is an EM technique that measures natural electric and magnetic fields at the surface to infer subsurface electrical resistivity. MT field natural sources originate from lightning discharges and magnetospheric current systems due to solar activity. MT data is collected at different locations and frequencies to distinguish spatial variations in resistivity. This is possible because EM field penetration decays exponentially according to the frequency and resistivity of the medium (Schenkel et al., 1999). The Magnetotelluric method is useful for deep detection of inclined low EC features influencing groundwater flow, but Allen (2005a) suggested that both the theory and practice of imaging are complicated and require experienced and competent operation.

5.4.4. Seismic Methos

Seismic energy generated as shock waves at the surface of the Earth (normally by explosion or vibration) travels through the subsurface and can be reflected or refracted back to the surface by geological layers or structural boundaries, and subsequently recorded at the surface by geophones. The time delay between generation of the shock waves and their arrival at the geophone is processed to create images of subsurface layers and structures (Drummond, 2002). Seismic techniques have been widely used in large sedimentary basins to investigate stratigraphic and structural features for oil and gas exploration but these surveys, focused on deep geological structures, have commonly not resolved near-surface features. However, both reflection and refraction techniques can be scaled to the target depth of interest (Drummond, 2002) and can therefore be applied to the identification of palaeovalleys or to detailed investigations of their stratigraphic architecture. Seismic reflection surveys are best suited to identifying the geometry of interfaces in regolith or bedrock and would be preferred for the identification of palaeovalley drainage patterns, depth of incision into bedrock and location of thalweg. Refraction surveys are best suited to identifying variations in the composition of the palaeovalley stratigraphic and structural features, but refraction surveys often provide a less detailed geometrical image than reflection profiles (Drummond, 2002).

Holzschuh (2002) has suggested that seismic surveying offers excellent has the potential to delineate palaeovalley features, especially where such features can be otherwise masked by the affects of hypersaline palaeochannel groundwater on other geophysical techniques such as electromagnetic and electrical methods. Holzschuh (2002) reported comparative results of compressional-wave (P) and shear-wave (S) seismic reflection techniques, refraction seismic and gravity surveys in an investigation of the palaeochannel aquifer of the Lefroy Palaeovalley tributary at Argo in the eastern Yilgarn (WA). The palaeovalley at Argo has a basal early-mid Eocene fluvial sand and gravel aquifer with lignite overlain by upper Eocene marginal marine sediments and an Oligo-Miocene fluvio-lacustrine unit. Argo palaeochannel groundwaters are hypersaline, acidic and moderately oxidising (Holzschuh, 2002). An initial 12-channel hammer-source survey was used to optimise acquisition parameters and the survey was conducted with a 48-channel system using a combination of explosive and hammer shot sources, which was specifically scaled for the site investigation. Ten metres of unsaturated loose sand at the surface was a major impediment for subsurface imaging and precise processing was required with accurate static and normal moveout corrections. Deconvolution enhanced recognition of the aquifer and other palaeovalley reflectors and both reflection and refraction P-wave results correlated well in defining boundaries of the watertable, compaction changes in palaeovalley sediments, sand and gravel aquifers, saprolite layers, and weathered and unweathered bedrock. Hammer and explosive sources had similar P-wave signal characteristics and both defined the aquifer and bedrock. S-wave reflection showed high lateral and vertical resolution of the saprolite, the sand and gravel aquifer and shallow clays above the aquifer. The refraction survey did not identify the bedrock boundary.

Hou et al. (2000) indicated that both reflection and refraction seismic surveys across the Tallaringa and Garford Palaeovalleys of the Gawler Craton were successful in defining the position of the channel but did not accurately define the channel base.

5.4.4.1. Seismic Methods for Groundwater

Most readily available seismic data is focussed on deep subsurface structures in sedimentary basins and is only useful for identifying or characterising deep aquifers and their groundwater resource potential. However, Holzschuh (2002) was able to scale both reflection and refraction seismic methods to identify palaeovalley profiles, palaeochannel stratigraphic characteristics and the location of the watertable in a Yilgarn palaeovalley (as detailed above). Further examples of the use of shallow refraction seismic surveys for groundwater exploration are available from the United States Geological Survey (USGS) Office of Groundwater, Branch of Geophysics (http://water.usgs.gov/ogw/bgas/) (Allen, 2005a).

5.4.5. Magnetics

Magnetic surveys can be used to investigate the subsurface by exploiting the natural variation in the magnetic properties of minerals. Typically the amplitude of the earth's magnetic field is measured at points along well-defined survey transects which cover the area of interest. The magnetic field induced in magnetically susceptible geologic materials (by the Earth's magnetic field) and the remanent magnetism of these materials, are of most interest as these are directly related to the magnetic susceptibility, spatial distribution and concentration of these subsurface materials. The effects of the Earth's magnetic field and other smaller magnetic fields (such as those caused by solar, atmospheric and cultural sources) must be removed from the original observations prior to analysis and interpretation (Brodie, 2002). Magnetic surveys can be ground-based (person-carried or vehicle-borne) or airborne along predetermined survey lines, with perpendicular tie lines and coeval data recorded from a stationary base magnetometer, which allow for adjustment of temporal variations in the Earth's magnetic field. Line spacing (closer lines means higher resolution) and orientation (perpendicular to feature of interest) are dependent on the size, depth and geometry of the target feature. For example, narrow shallow features have narrow magnetic anomalies, whereas larger, deeper features have broader, but often more subtle, anomalies (Brodie, 2002). For airborne surveys the minimal possible safe flying height enhances resolution and should be matched with suitably spaced flight lines. Many steps of data processing, post-processing and enhancement are available, and the final survey results are mainly presented as stacked line profiles, contour maps, colour or grey-scale images or bipole plots of profile data. Images have become the most popular form of presentation because the digital data can be easily manipulated and interfaced with other datasets in GIS (Brodie, 2002).

Brodie (2002) presented an example of magnetic surveying near West Wyalong, New South Wales, where palaeovalleys are delineated in some detail in a grey-scale magnetic image due to an abundance of maghemite in the palaeovalley fill. However, Jenke (reported in Holzschuh, 2002) suggested that magnetics data are generally not reliable for groundwater exploration due to high ambient magnetic noise.

5.4.5.1. Magnetics for Groundwater

Total magnetic intensity (TMI) sensors do not correlate directly to the abundance or salinity of groundwater, only to the presence of iron minerals such as haematite, goethite, maghemite and magnetite in the subsurface. Allen (2005a) suggested that TMI can be used for groundwater exploration where water occurs in upland fractured rock aquifers. Additionally, magnetic surveys can also identify palaeovalleys where there is a strong contrast in iron mineral content between palaeochannel and surrounding sediments. Airborne magnetic survey data is widely available across Australia, although site-specific ground-based surveys are advised for detailed investigations (Allen, 2005a). Ground-based magnetic instruments are typically integrated with GPS and moving map displays. Jenke (1996) indicated that high ambient magnetic noise in palaeochannel sediments with saline groundwater seriously inhibits the effectiveness of magnetics data for groundwater exploration.

5.4.6. Gamma-Ray Spectrometry

Gamma-ray spectrometry measures the abundance of potassium (K), thorium (Th) and uranium (U) in earth materials by detecting and counting gamma-rays emitted by natural radioactive decay of these elements, directly for K and via daughter nuclides for Th and U. Data collection is commonly undertaken by low-flying aircraft with sodium iodide scintillation crystal detectors, along flight lines spaced according to cost constraints and resolution requirements. Gamma rays are: strongly attenuated by minerals; moderately attenuated by water and barely attenuated by vegetation or air. Thus, they emanate from the top 30 centimetres of dry rock and soil (Wilford, 2002). Potassium has a relatively high crustal abundance (2.3%) but uranium and thorium are much less common; all three elements can occur in a variety of rocks and minerals – K in crystalline and sedimentary rocks and weathering products, U in crystalline and sedimentary rocks and accessory minerals, and Th in accessory (commonly resistant) minerals (Wilford, 2002). Data are processed, corrected and displayed mainly as false-colour images of K (expressed as percent) and Th and U (expressed as parts-per-million).

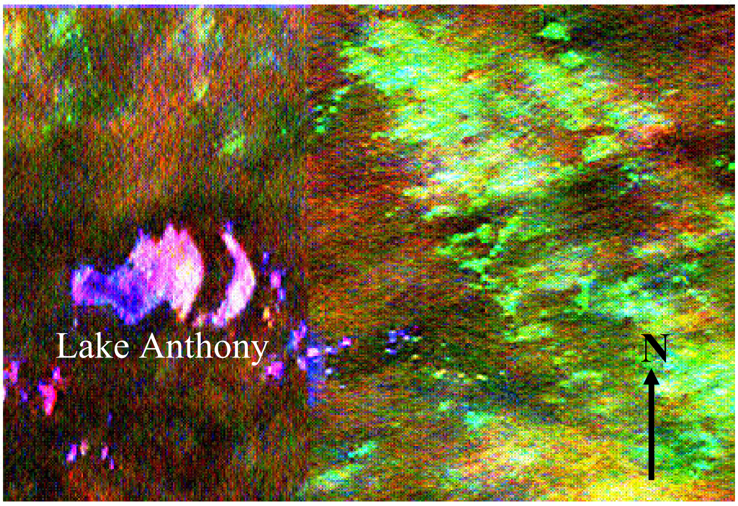
Gamma-ray spectrometry can be useful in discriminating landscape and geological features because of differences in K, U and Th distribution in rocks and differences in pathways during weathering, pedogenesis, transport and deposition (Figure 5.8). Gamma-ray response over an actively eroding landscape will reflect bedrock mineralogy and geochemistry whereas response over stable landforms will reflect soil/regolith signatures (Wilford, 2002). Digital image data can be draped over DEM data to great effect in separating bedrock and regolith responses. Very limited examples of gamma-ray spectrometry data relating to palaeovalley exploration were located. Wilford (2000) suggested that both K and Th are likely to be low in palaeovalley calcretes.

From an understanding of the geochemical characteristics of K, U, and Th gamma-ray data can be interpreted in terms of lithologic and geologic characteristics. However, as the signal is only derived from the upper 30 centimetres of the subsurface the stand-alone use of radiometric surveys has little potential for delineating groundwater characteristics.

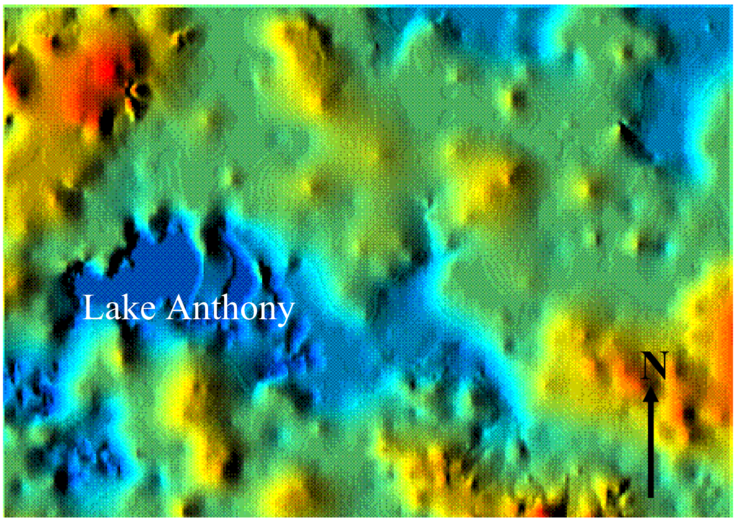
5.4.7. Magnetic Resonance Sounding Method for Groundwater

Magnetic resonance sounding can directly detect aquifer properties, such as water content and permeability. The method is similar to that used for medical magnetic resonance imaging (MRI) and works by measuring excitation of hydrogen protons in water molecules. However the energy is supplied by the weak and variable magnetic field of the Earth, rather than by using powerful magnets as with MRI. Some magnetic resonance systems generate their own magnetic field at a specific frequency by a current loop (Geo-hydrology, 2007). The amplitude of the magnetic field produced by the excited protons is proportional to the water content (porosity), and the time constant of the decay is linked to the mean pore size and hence to permeability. The response from saturated clay layers can be filtered out. The method is one of the few geophysical methods which can directly detect subsurface water and estimate both porosity and permeability. However, it cannot be used where rocks are highly magnetic or where cultural electromagnetic noise occurs (power lines, pipelines, fences etc). The magnetic resonance method, dependent as it is on H protons in water molecules, does not discriminate between fresh and saline groundwater (Geo-hydrology, 2007).

a)



b)



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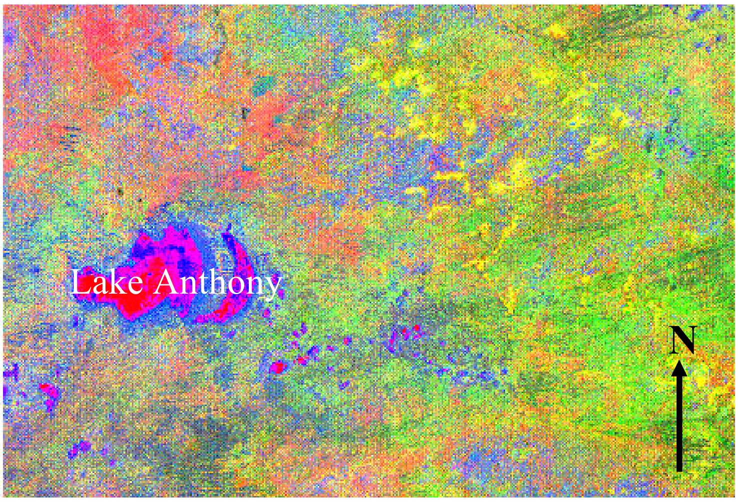

Figure 5.8: *Radiometric image for part of the central Gawler Craton near Lake Anthony and the Challenger gold mine (A), compared with the digital elevation model and Landsat TM image (after Hou, 2001). Figure obtained from Primary Industries and Resources South Australia and used with their express permission.*

As with TEM, the magnetic resonance signal is attenuated by conductive saline groundwater, so cannot be used for investigating deep aquifers under saline cover (Allen, 2005a). This may impact its potential for investigating palaeochannel facies aquifers in palaeovalleys. Additionally, it is a relatively expensive technique, and may thus not be a practical geophysical option in many circumstances.

5.4.8. Very Low Frequency Method for Groundwater

Very low frequency (VLF) techniques use signals similar to those transmitted for submarine navigation, in order to determine vertical or steeply inclined variations in electrical conductivity in the subsurface. The ability of the method to detect such variations depends on their orientation relative to the direction of the VLF source (Allen, 2005a). VLF methods are best utilised for identifying fracture zones in resistive bedrocks which may represent aquifers. However, its applicability for palaeovalley aquifer investigations is probably limited.

5.4.9. Electrokinetic Method for Groundwater

Electrokinetic (EK) potentials can occur across boundaries between a fluid electrolyte and the mineral grains or rock particles in fractured rocks or porous media (Kim et al., 2004). Electrokinetic potentials are generated by:

- Fluid-flow processes;
- Heat fluxes;
- Pressure sources; and
- Diffusion potentials.

The EK technique uses a seismic source to generate charges in water molecules, which then permeate through the sediment and create voltages at the surface which are picked up by a geotechnical array (Allen, 2005a). EK measures the variation in hydraulic conductivity of saturated subsurface layers with depth from seismically induced time-varying electromagnetic response in saturated aquifers. The seismic source is a drop weight or hammer on a plate which has two pairs of receiver electrodes aligned symmetrically about it, with vertical resolution dependant on the frequency of the seismic energy as well as the permeability contrast within a saturated aquifer. In most situations a hammer source is sufficient and azimuthal soundings at each measurement station monitor anisotropy. To relate hydraulic conductivities to depth, the seismic velocity of subsurface layers and their conductivities must be independently derived, for example by calibration against boreholes, from TDEM soundings, or from shallow seismic refraction surveys (Zetica, www.zetica.com).

Electrokinetic data are presented as 1-D plots of the measured EK signal in millivolts versus depth for the two channels positioned either side of the source, which are used to calculate the approximate permeability (in metres-per-day) for saturated bedrock aquifers. From an EK sounding profile or a series of profiles, 2-D sections of permeability versus depth can be constructed by extrapolating the 1-D models. Permeability maps can be produced for individual depth slices, if sufficient data is collected. However, the EK method is controversial (Allen, 2005a) with some researchers claiming that seismically induced Rayleigh-wave signals are the main source of EK signals. Kim et al. (2004) emphasised difficulties in interpreting EK results, and it is likely to be of limited use in palaeovalley groundwater studies.

5.4.10. Ground Penetrating Radar Method for Groundwater

Ground penetrating radar (GPR) is a relatively new and promising technique for remote detection of soil moisture or groundwater by person-carried, vehicle-borne or vehicle-towed equipment. Huismann et al. (2003) have reviewed GPR for measuring subsurface groundwater and soil moisture parameters. Dielectric permittivity is anomalously high for water at radar frequencies, thereby allowing detection of subsurface moisture from radar characteristics such as:

- Reflected wave velocities;
- Ground wave velocities;
- Transmitted wave velocities (i.e., between boreholes); and
- Surface reflection coefficients.

However, for most palaeovalley studies, GPR signals will not penetrate to sufficient subsurface depths to delineate either palaeovalley architecture or features associated with groundwater resources.

5.5. DRILLING

Ultimately drilling is required to truly define the nature and extent of palaeovalley infilling sediments and the characteristics and quantity of their groundwater resources. Mapping and remote sensing techniques can certainly delineate the pattern of palaeodrainage networks and the surface extent and expression of individual palaeovalleys. Some geophysical techniques can also delineate the subsurface distribution and perhaps the stratigraphic architecture of palaeovalleys. However, palaeochannel facies (i.e., the main palaeovalley aquifer) are located in the deepest incised part of the palaeovalley and to thoroughly understand the palaeochannel age, stratigraphy, sedimentology, geometry and aquifer characteristics requires information and samples which can only be obtained from drilling. Required drilling depths are likely to be relatively modest (generally less than 200 metres) but palaeovalley sediments are highly variable in their lithologic composition, degree of compaction and cementation, and groundwater saturation. These factors make drilling of palaeovalley groundwater systems a complex and challenging process.

Johnson et al. (1999) used aircore drilling during investigation of palaeovalleys in the northern Yilgarn Craton; the method provided representative samples of sediments and groundwater from the palaeovalleys, although the latter may be contaminated by the air-mist drilling technique. Aircore drilling may fail in loose sand-rich sediment when large differential hydrostatic pressures between groundwater and the drilling rods can induce running sands to flow (into the drill rods). This necessitates frequent withdrawal and cleaning of the drill stem or abandonment of drilling (Johnson et al., 1999). Mud-rotary drilling is effective in penetrating clay and loose sand and casing can be inserted in the hole to enable groundwater sampling (P. Commander, pers. comm. 2008).

Clarke et al. (1992) suggested that rotary auger drilling is unsuitable for drilling piezometer or groundwater investigation bores because it smears clays on the walls of holes and therefore reduces the measured hydraulic conductivity. They suggested that rotary air blast (RAB) drilling is preferable for drilling in these geologic materials. However, RAB drilling may fail in loose sands, and aircore drilling with narrow diameter casing inserted down the rods is generally far superior (Johnson et al., 1999).

5.5.1. Borehole Logging

Geophysical investigations of the subsurface geometry and stratigraphic architecture of palaeovalleys are of dubious veracity unless controlled or calibrated by cross-sectional drillhole data.

Similarly, groundwater geophysical imaging is of limited value unless calibrated by borehole data which can be derived from:

- Lithological logs and samples;
- Groundwater samples; and
- Various down-hole geophysical logging techniques.

The latter are particularly important for deep boreholes. Some geophysical logging is conducted during drilling, which is necessary for techniques designed to measure groundwater or aquifer properties before they become disturbed due to drilling. Other geophysical logging can be conducted following completion and casing of a borehole (Allen, 2005a).

A basic borehole logging package consists of a winch, a logger and an array of logging tools, which are used for various purposes. For example, gamma tools differentiate clayey and sandy units, whereas electrical conductivity tools measure clay and salinity contents. Geo-electric tools are used for measuring down-hole electrical conductivity (EC) unless the hole is cased, whereby induction electromagnetic tools are required. Calliper tools are used to locate borehole blowouts that may interfere with gamma and EC recordings, and also indicate unstable lithologic zones. Sonic and neutron tools can determine porosity and effective porosity, and gamma-gamma density tools measure rock density which helps to characterise important aquifer properties (Allen, 2005a). Resistivity or induction tools are commonly used for palaeovalley-related investigations (P. Commander, 2008, pers comm.).

Various down-hole tools are used to sample groundwater and temperature within the borehole, but movement of water up or down the borehole can compromise the integrity or accuracy of samples and measurements. Acoustic and optical televiewers can be used to view the rock and casing of drillholes, which aids in identifying the location and orientation of aquifer characteristics. Tools such as heat-pulse flow meters and EM flow meters are hydro-physical logging techniques that can determine where water enters and leaves boreholes, assisting in the assessment of aquifer cross-contamination. Other down-hole flow-meter tools also exist. Allen (2005a) suggested that to identify some features, such as a perched aquifer, logging must be conducted before the aquifer is disturbed, which can be achieved by using an auger or penetrometer that contains internal logging tools. However, P. Commander (pers. comm. 2008) suggested that perched groundwater can be identified using resistivity tools in mud-dominated holes, although this may be difficult in deeper palaeovalleys.

5.6. GROUNDWATER ISOTOPES

The advent of mass spectrometric groundwater analyses has led to easier, more accurate and precise measurement of low-abundance stable and radioactive isotopes. As with many geoscientific studies this has allowed routine stable isotope tracing of groundwater sources, sinks and migration pathways. Measurement of radioactive isotopes dissolved in groundwater has also provided opportunities for dating the age of groundwater, helping in the interpretation of groundwater origin and evolution in many parts of the world. The use of stable isotopes in groundwater studies is a major research topic in itself and, because of limitations of time and space, a comprehensive review is not attempted here. Initial information on these topics is provided by Clark and Fritz (1997), Cook and Herczeg (2000) and Kendall and McDonnell (1998).

5.7. GROUNDWATER DATING

Numeric dating of dissolved ions in groundwater can provide crucial information on the source and migration pathway of groundwater, as well as indicating the entry time of groundwater into an aquifer system. This allows quantitative estimates of timing and rates of recharge and throughflow, all of which are crucial for determining the sustainability of palaeovalley groundwater resources. At the simplest level, dating by radioactive decay compares the ratio of radioactive isotope and daughter product of a sample with the initial ratio, and the time between the two is determined by the half life of the radioactive isotope. Unfortunately there are often considerable complexities of gain or loss through time of either radioactive parent or daughter product by non-radioactive-decay methods which can result in incorrect age calculations.

5.7.1. Radiocarbon Dating

Radiocarbon (^{14}C) dating has been used since the 1950's, with radiogenic measurement initially by scintillometer beta-counting and, more recently, by accelerator mass spectrometry (AMS), which allows more precise atom-counting from smaller samples. Radiocarbon is produced in the atmosphere by cosmic-ray interaction with ^{14}N but the production rate has varied with time, requiring calibration of the technique for accurate numeric dating. Radiocarbon produced in the atmosphere is incorporated into the products of an enormous number of organic and inorganic reactions. There are numerous complexities due to fractionation and subsequent addition or loss of younger or older carbon due to the extreme reactivity of many carbon compounds. Of particular and universal concern is the incorporation of young carbon, relatively rich in ^{14}C, into old samples, resulting in anomalously young numeric ages. The AMS technique allows more careful sample selection and pre-treatment, which can help reduce errors due to sample contamination, but the instrumental ability to measure ^{14}C atoms generally exceeds the ability to obtain samples which are uncontaminated by ^{14}C from younger sources.

Groundwater dating by ^{14}C has particularly targeted dissolved carbonate but can also target dissolved organic carbon (DOC). A number of previous studies have used this technique to assess the age of palaeovalley groundwater, e.g., Cresswell et al., 1999; Harrington et al., 1999; Harrington et al., 2002. Because of the very slow recharge rates, diffusion can become a significant component of carbon transport through the aquifer, which can result in higher ^{14}C than expected with consequent under estimation of age and over estimation of recharge rates (Cresswell et al., 1999). Additionally, mineral reactions with groundwater can involve carbon exchange which may also alter the $^{14}C/^{12}C$ ratio, leading to anomalous age estimations; dissolution of ancient carbonates in particular will overestimate the age. However, when used with careful regard to contamination from other carbon sources ^{14}C dating can be an extremely useful technique for dating groundwater of about 30,000–50,000 years old.

5.7.2. Chlorine 36

Chlorine is a hydrophilic non-reactive element that has a number of characteristics that make it a useful chemical tracer for hydrologic studies. In particular, chlorine:

- Is highly soluble;
- Exists in nature as a conservative non-sorbing anion;
- Does not participate in redox reactions; and
- Has a relatively easily identifiable source, e.g., seawater.

Three isotopes occur naturally: stable ^{35}Cl (75.8%) and ^{37}Cl (24.2%), and radioactive ^{36}Cl. The ratio of ^{36}Cl to stable Cl in the environment is about 700 x 10^{-15} to 1. ^{36}Cl is produced both in the atmosphere (by spallation of ^{36}Ar by interactions with cosmic ray protons) and in subsurface environments, e.g., as a result of neutron capture by ^{35}Cl or muon-capture by ^{40}Ca). ^{36}Cl decays to ^{36}S and to ^{36}Ar, with a combined half-life of 308,000 years, which makes it suitable for dating in the range of 60,000–1 million years (Kendall et al., 2004). ^{36}Cl abundance is reported as the atomic ratio of ^{36}Cl to total chloride, which is always quite small in natural waters, ranging from 10^{-15}–10^{-11}. The four orders of magnitude range of $^{36}Cl/Cl$ ratios is due to several factors. Over geologic time equilibrium is established between subsurface in-situ production of ^{36}Cl and its decay (similar to the secular equilibrium of U isotopes), with the equilibrium value dependant on the U and Th concentrations in the aquifer (Kendall et al., 2004).

^{36}Cl has been used to date old ground water in confined aquifers by consideration of the effect of radioactive decay on measured $^{36}Cl/Cl$ ratios; the method has been successfully applied to groundwater in the Great Artesian Basin (Bentley et al., 1986; Torgerson et al., 1991). Potential changes to the $^{36}Cl/Cl$ ratio due to non-radioactive decay include possible addition of stable Cl isotopes to water by water-rock reactions, ion filtration, or mixing with other water which has higher chloride contents. Determining the initial $^{36}Cl/Cl$ ratio can also be difficult due to the wide range of possible sources. Non-radioactive addition of Cl can be evaluated by measurement of the Cl and other ionic concentrations in the water, and original source values can be estimated using present-day local values. Subsurface production of ^{36}Cl requires accurate assessment of the U and Th concentrations in the aquifer. For determining groundwater transit times between two sampling locations the value measured at the up-gradient location is used as the source value (Kendall et al., 2004).

The $^{36}Cl/Cl$ ratio can be used to estimate the age of groundwater under the following conditions (Cresswell et al., 1999):

- If the only sink for ^{36}Cl in the groundwater is radioactive decay;
- If the only source for additional ^{36}Cl is subsurface production (or that other sources can be identified and quantified); and
- If the initial $^{36}Cl/Cl$ ratio can be quantified.

An investigation of the age of various groundwater samples in palaeovalleys in arid Australia (Cresswell et al., 1999) indicated extremely ancient episodic recharge on 10^4–10^5 year timescales. Clearly however, further $^{36}Cl/Cl$ dating of arid zone palaeovalley groundwater is required to better understand the origin and evolution of these aquifer systems.

5.8. GROUNDWATER MODELLING

As with stable isotope studies, groundwater modelling is a major research topic in itself and, because of limitations of time and space, a comprehensive review has not been attempted as part of this study. A large number of modelling approaches are possible and an initial source of information on the topic is provided by Kresic (2006). Turner et al. (1993) have evaluated various numerical modelling approaches during study of palaeovalley groundwater systems, enabling quantitative estimates to be made of various groundwater parameters including recharge and discharge.

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